Lecture 2 - Experimental performance investigation of wave energy converters

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2015

Lecture 01:
Introduction to Wave Energy Utilization
Wave energy technologies

Topics:
- Why wave energy?
- The history
- The resource
- Activities around the world
- Policies
- Organizations
- Test sites
- Funding schemes
- Major collaborative projects
- Considerations on design of WECs
- Staged development approach
- Overview of technologies

WAVE ENERGY AT AALBORG UNIVERSITY

JENS PETER KOFOED
AALBORG UNIVERSITY
DEPARTMENT OF CIVIL ENGINEERING
DIVISION OF RELIABILITY, DYNAMICS AND MARINE ENGINEERING
WAVE ENERGY RESEARCH GROUP

AALBORG UNIVERSITY
DENMARK

AALBORG UNIVERSITY
AALBORG · ESBJERG · COPENHAGEN

KEY FIGURES 2014

Regular students	20.115
International students	3.178
Part-time students	2.012
PhD students [2013]	1.108
Academic staff (full-time)	2.080
Academic staff (part-time)	740
Administrative staff (full time)	1.447
Administrative staff (part-time)	381
Research publications [2013]	5.060
Financing (DKK million)[2013]	2.560,2

Student facts and figures
Aalborg University awards Bachelors, Master's, Ph.D. and Doctoral degrees. In 2013 180 students received a Ph.D. degree. More than 19.000 students are enrolled at Aalborg University. Approximately 4.900 students are enrolled at the Faculty of Humanities, 5.577 students at the Faculty of Social Sciences and 8.600 at the Faculty of Engineering, Science and Medicine.

http://www.aau.dk/

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Energy at Aalborg University

HUMANITIES	SOCIAL SCIENCES	ENGINEERING AND SCIENCE	MEDICINE
Department of Communication and Psychology	Department of Sociology and Social Work	Department of Architecture, Design and Media Technology	Department of Health Science and Technology
Department of Culture and Global Studies	Department of Culture and Global Studies	Department of Electronic Systems	Department of Clinical Medicine
Department of Learning and Philosophy	Department of Learning and Philosophy	Department of Learning and Philosophy	Department of Learning and Philosophy
	Department of Business and Management	Department of Business and Management	Department of Business and Management
	Department of Political Science	Department of Civil Engineering	
	Department of Law	Department of Computer Science	
		Department of Energy Technology	
		Department of Physics and Nanotechnology	
		Department of Chemeistry and Bioscience	
		Department of Mathematical Sciences	
		Department of Mechanical and Manufacturing Engineering	
		Center for Industrial Production	
		Department of Development and Planning	
		Danish Building Research Institute	

Aalborg Model for Problem based Learning and Research

http://mariethurah.dk/AAU/energiuniversitetet_web.pdf

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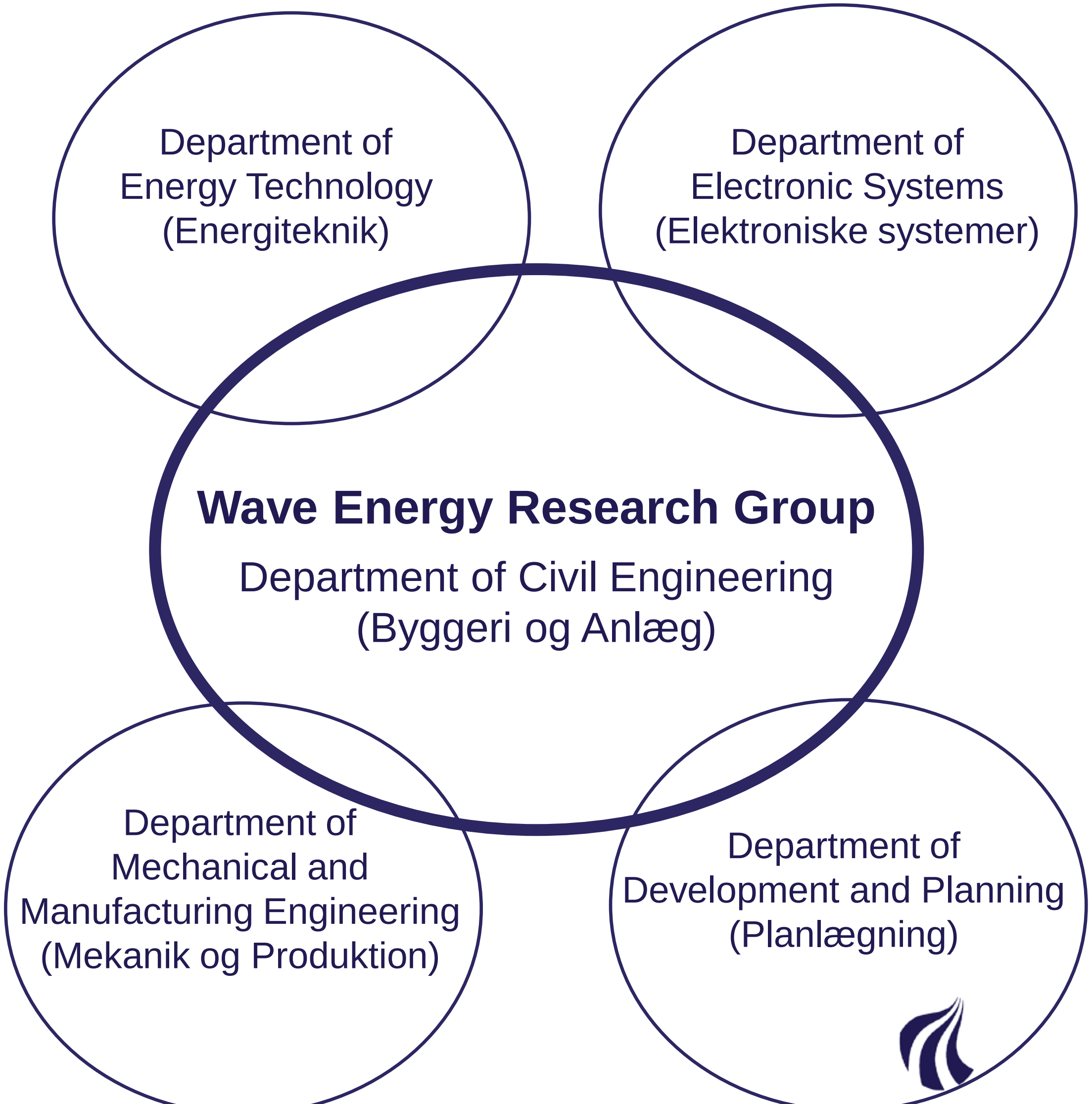
http://issuu.com/blueaau/docs/issuu_detbl__universitet_32sider_20

Wave Energy at AAU



http://www.waveenergy.civil.aau.dk/

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DENMARK

Key persons:

Jens Peter Kofoed
Head of the Wave Energy Research Group

Peter Frigaard
Head of Department of Civil Engineering

Wave Energy Research Group at Aalborg University (AAU) performs R&D within the wave energy field and has established itself as a R&D hub connecting all Danish, as well as number of international, concepts. Since the group started its activities about 20 years ago, AAU has worked with wave theory, resource assessment and numerical modelling; with the hydrodynamics, power conversion systems and mechanical parts of WECs; and with the testing and evaluating of 25 WECs at AAU wave tank facilities and in real sea.

Department of Civil Engineering

http://www.civil.aau.dk/

Persons directly involved in Wave Energy, April 2015

Management and administration


Peter Frigaard
Head of Department


Jens Peter Kofoed
Associate Professor


Kim Nielsen
Associate Professor


Anne Stuhlmann Schmidt
Senior Secretary

Experimental work


Amelie Tetu
Associate Professor


Arthur Pecher
Post doc


Morten Kramer
Associate Professor


Nikolaj Holk,
Semi-skilled worker


Niels Drustrup
Assistant Engineer

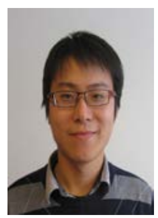
Foundation


Lars Bo Ibsen
Professor


Evelina Vaitkunaite
PhD student

Control

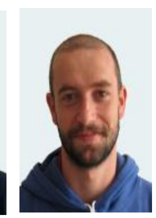

Søren Nielsen
Professor


Zili Zhang
PhD student

Loads, software


Thomas Lykke
Associate Professor


Morten Møller
PhD student


Francesco Ferri
Post doc


Jonas Bjerg
PhD student


Pau Mercadé Ruiz
PhD Fellow

Materials, concrete


Luis Pedro Esteves
Postdoc


Eigil Sørensen
Collaboration Partner

Reliability


John Dalsgaard
Professor


Simon Ambühl
Post doc

Structural design


Lars Damkilde
Professor


Michael Jepsen
Research Assistant

Waves, wind, solar, ...


Julia Chozas
Research Assistant


Lucia Margheritini
Associate Professor


Morten Thøtt
PhD student

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Additional departments at AAU involved in Wave Energy

Besides Department of Civil Engineering (Byggeri og Anlæg)

- Department of Energy Technology (Energiteknik)
  Henrik Clemmensen, Torben Andersen, Anders Hedegaard
  http://www.et.aau.dk/



- Department of Electronic systems (Elektroniske Systemer)
  Palle Andersen, Kirsten Nielsen, Tom Pedersen
  http://www.es.aau.dk/



- Department of Development and Planning (Planlægning)
  Karl Sperling, Henrik Lund, Brian Vad Mathiesen
  http://www.plan.aau.dk/



- Department of Mechanical and Manufacturing Engineering
  Ole Thybo Thomsen, Erik Lund, Martin Heide Jørgensen
  http://www.m-tech.aau.dk/



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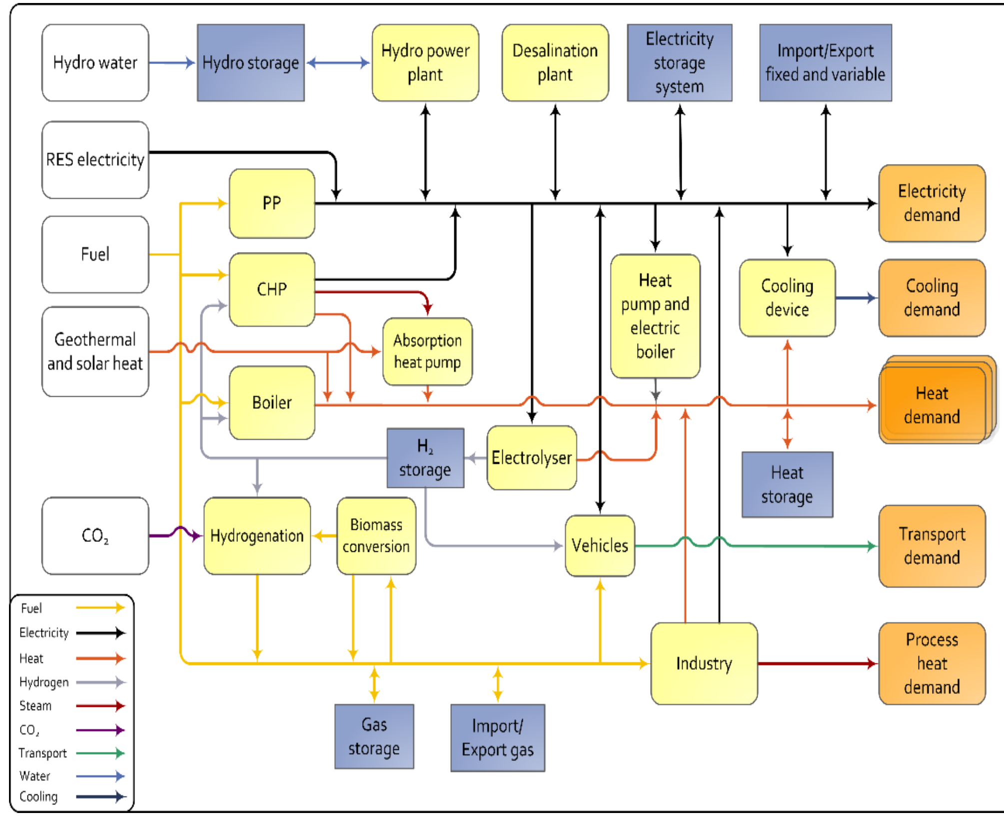
Department of Development and Planning

STRATEGISK ENERGIPLANLÆGNING
SKAL SIKRE GRØN FREMTID

Fremtidens energiscenarier tegner godt, hvis staten, regionerne og kommunerne i fællesskab kan implementere et nyt grønt energisystem i Danmark. Kommunal strategisk energiplanlægning handler om at udvikle kompetencer til at tænke langsigtet og på tværs af sektorer, så man kan få et energisystem, der kan skabe udvikling lokalt og regionalt.

40 PROBLEMBASERET FORSKNING



http://www.energyplan.eu/getstarted/

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Karl Sperling


Henrik Lund

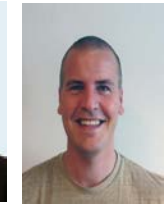

Brian Vad

Waves, wind, solar, ...

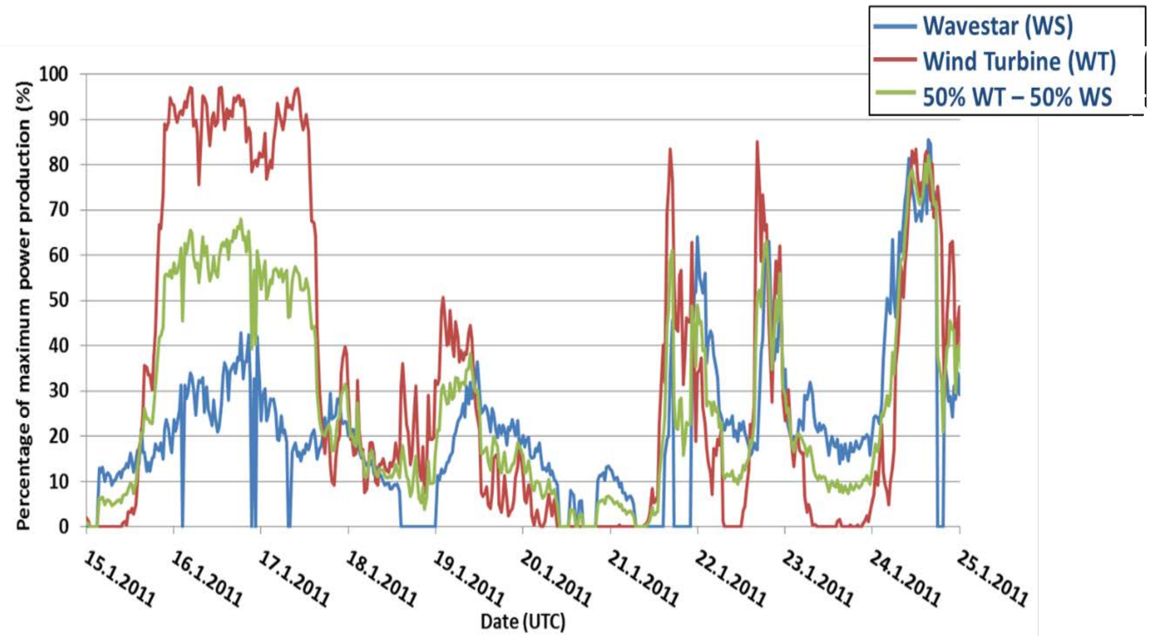
Department of Civil Engineering

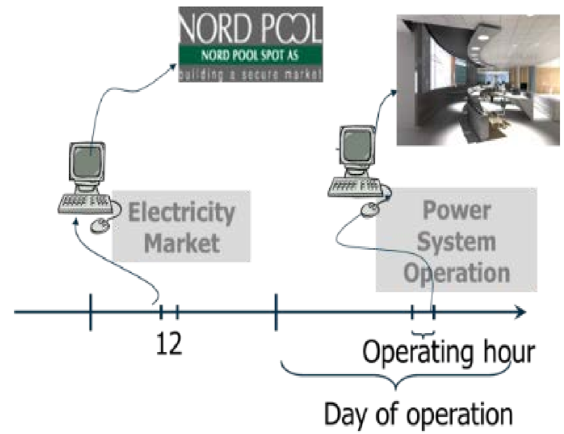

Julia Chozas
Research Assistant


Lucia Margheritini
Associate Professor


Morten Thøtt
PhD student

Benefits by combining wind turbines with wave energy





- ✓ Short-term forecasting (H=12-36 hours) of wave parameters 10% more accurate than for wind parameters
- ✓ Predictability of WECs individual power production 5%-10% more accurate than for wind turbines
- ✓ Short-term forecasting of wind production 6% improved when wave production added
- ✓ Best combination 50% wave/50% wind: → barely no lack of production, small standard deviation, less fluctuating power than wind.

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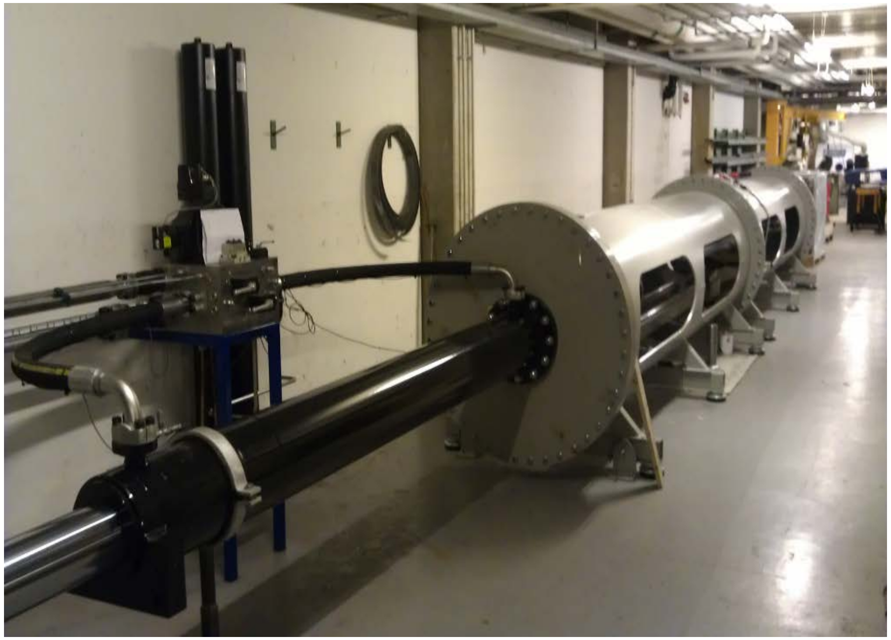
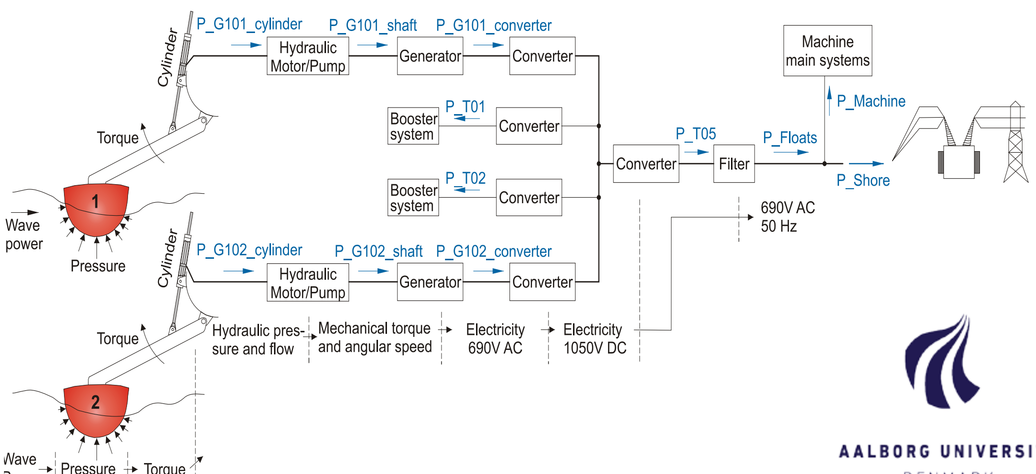
Department of Energy Technology





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Henrik Clemmensen

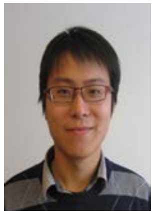
Torben Andersen

Anders Hedegaard

Department of Civil Engineering

Control

Søren Nielsen
Professor



Zili Zhang
PhD student

Increase in the power production by optimized control

$$H(\mathbf{z},\mathbf{f}_c,\boldsymbol{\lambda},t) = \dot{\mathbf{v}}^T(t)\mathbf{f}_c(t) + \boldsymbol{\lambda}^T(t)\Big(\mathbf{A}\,\mathbf{z}(t) + \mathbf{B}\big(\mathbf{f}_e(t)-\mathbf{f}_c(t)\big)\Big) \quad , \quad \boldsymbol{\lambda}(t) = \begin{bmatrix} \boldsymbol{\lambda}_v(t) \\ \boldsymbol{\lambda}_{\dot v}(t) \\ \boldsymbol{\lambda}_r(t) \end{bmatrix} \qquad (51)$$

$\boldsymbol{\lambda}(t)$ is the co-state vector. The Euler-Lagrange stationarity conditions for optimal control become, (Naidu 2002)

State vector equation:

$$\dot{\mathbf{z}}(t) = \frac{\partial H}{\partial \boldsymbol{\lambda}} = \mathbf{A}\,\mathbf{z}(t) + \mathbf{B}\big(\mathbf{f}_e(t) - \mathbf{f}_c(t)\big) \qquad (52)$$

Co-state vector equation:

$$\dot{\boldsymbol{\lambda}}(t) = -\frac{\partial H}{\partial \mathbf{z}} = -\mathbf{M}\mathbf{B}\,\mathbf{f}_c(t) - \mathbf{A}^T\boldsymbol{\lambda}(t) \qquad (53)$$

Stationarity condition on the control force:

$$\frac{\partial H}{\partial \mathbf{f}_c} = \dot{\mathbf{v}}(t) - \mathbf{B}^T\boldsymbol{\lambda}(t) = \dot{\mathbf{v}}(t) - \mathbf{M}^{-1}\boldsymbol{\lambda}_{\dot v}(t) = \mathbf{0} \qquad (54)$$

Terminal condition on the co-state vector:

$$\boldsymbol{\lambda}(t_1) = \mathbf{0} \qquad \big(\boldsymbol{\lambda}_v(t_1) = \boldsymbol{\lambda}_{\dot v}(t_1) = \mathbf{0}\ ,\ \boldsymbol{\lambda}_r(t_1) = \mathbf{0}\big) \qquad (55)$$

Above, $\frac{\partial H}{\partial \boldsymbol{\lambda}}$, $\frac{\partial H}{\partial \mathbf{z}}$ and $\frac{\partial H}{\partial \mathbf{f}_c}$ denote column vectors storing the components $\frac{\partial H}{\partial \lambda_j}$, $\frac{\partial H}{\partial z_j}$ and $\frac{\partial H}{\partial f_{cj}}$. The component equations of (53) read

$$\left.\begin{aligned} \dot{\boldsymbol{\lambda}}_v(t) &= \ \ \mathbf{k}\mathbf{M}^{-1}\boldsymbol{\lambda}_{\dot v}(t) \\ \dot{\boldsymbol{\lambda}}_{\dot v}(t) &= -\mathbf{f}_c(t) - \boldsymbol{\lambda}_v(t) - \mathbf{B}_r^T\boldsymbol{\lambda}_r(t) \\ \dot{\boldsymbol{\lambda}}_r(t) &= \ \ \mathbf{P}_r^T\mathbf{M}^{-1}\boldsymbol{\lambda}_{\dot v}(t) - \mathbf{A}_r^T\boldsymbol{\lambda}_r(t) \end{aligned}\right\} \qquad (56)$$

$$P_c = <\dot{\mathbf{v}}^T(t)\mathbf{f}_c(t)> = \frac{1}{T}\int_0^T \dot{\mathbf{v}}^T(t)\mathbf{f}_c(t)\,dt \ =$$

$$\frac{1}{2}\Big(\mathrm{Re}\big(i\omega\mathbf{V}^T\big)\mathrm{Re}\big((\mathbf{k}_c - \omega^2\mathbf{m}_c + i\omega\mathbf{c}_c)\mathbf{V}\big) + \mathrm{Im}\big(i\omega\mathbf{V}^T\big)\mathrm{Im}\big((\mathbf{k}_c - \omega^2\mathbf{m}_c + i\omega\mathbf{c}_c)\mathbf{V}\big)\Big) \ =$$

$$\frac{1}{2}\Big(\mathrm{Re}\big(i\omega\mathbf{V}^T\big)\,\mathbf{c}_c\,\mathrm{Re}\big(i\omega\mathbf{V}\big) + \mathrm{Im}\big(i\omega\mathbf{V}^T\big)\,\mathbf{c}_c\,\mathrm{Im}\big(i\omega\mathbf{V}\big)\Big) \ =$$

$$\frac{1}{2}\omega^2\,\mathrm{Re}\big(\mathbf{V}^T\mathbf{c}_c\mathbf{V}^*\big) = \frac{1}{2}\omega^2\,\mathbf{V}^T\mathbf{c}_c\mathbf{V}^* \qquad (32)$$

$$f_{\mathbf{V}\dot{\mathbf{V}}}(\mathbf{v},\dot{\mathbf{v}}) = \frac{1}{(2\pi)^n\big(\det(\boldsymbol{\kappa})\big)^{1/2}}\exp\left(-\frac{1}{2}\begin{bmatrix}\mathbf{v}\\ \dot{\mathbf{v}}\end{bmatrix}^T\boldsymbol{\kappa}^{-1}\begin{bmatrix}\mathbf{v}\\ \dot{\mathbf{v}}\end{bmatrix}\right) \qquad (66)$$

where $\boldsymbol{\kappa}$ denotes the covariance matrix of $\big(\mathbf{V}(t),\dot{\mathbf{V}}(t)\big)$ given as

$$\boldsymbol{\kappa} = \begin{bmatrix} E\big[\mathbf{V}(t)\mathbf{V}^T(t)\big] & E\big[\mathbf{V}(t)\dot{\mathbf{V}}^T(t)\big] \\ E\big[\dot{\mathbf{V}}(t)\mathbf{V}^T(t)\big] & E\big[\dot{\mathbf{V}}(t)\dot{\mathbf{V}}^T(t)\big] \end{bmatrix} \qquad (67)$$

The mean power outtake from the cluster becomes

$$\bar{P}_c = E\big[\dot{\mathbf{V}}^T(t)\mathbf{F}_c(t)\big] = -E\big[\dot{\mathbf{V}}^T(t)(\mathbf{m}+\mathbf{m}_h)\ddot{\mathbf{V}}(t)\big] - E\big[\dot{\mathbf{V}}^T(t)\mathbf{k}\mathbf{V}(t)\big] +$$

$$2E\big[\dot{\mathbf{V}}^T(t)\mathbf{c}_c\dot{\mathbf{V}}(t)\big] + \int_{-\infty}^{t} E\big[\dot{\mathbf{V}}^T(t)\mathbf{h}_{r\dot{v}}(t-\tau)\dot{\mathbf{V}}(\tau)\big]\,d\tau \qquad (68)$$

Since, $(\mathbf{m}+\mathbf{m}_h) = (\mathbf{m}+\mathbf{m}_h)^T$ and $\mathbf{k} = \mathbf{k}^T$ it follows that

$$\left.\begin{aligned} E\big[\dot{\mathbf{V}}^T(t)(\mathbf{m}+\mathbf{m}_h)\ddot{\mathbf{V}}(t)\big] &= \frac{1}{2}\frac{d}{dt}E\big[\dot{\mathbf{V}}^T(t)(\mathbf{m}+\mathbf{m}_h)\dot{\mathbf{V}}(t)\big] = 0 \\ E\big[\dot{\mathbf{V}}^T(t)\mathbf{k}\mathbf{V}(t)\big] &= \frac{1}{2}\frac{d}{dt}E\big[\mathbf{V}^T(t)\mathbf{k}\mathbf{V}(t)\big] \qquad\qquad = 0 \end{aligned}\right\} \qquad (69)$$

where it has been used that the expectations $E\big[\dot{\mathbf{V}}^T(t)(\mathbf{m}+\mathbf{m}_h)\dot{\mathbf{V}}(t)\big]$ and $E\big[\mathbf{V}^T(t)\mathbf{k}\mathbf{V}(t)\big]$ are constant in time due to the stationarity of the involved vector processes.

Insertion of (69) into (68) provides the following result for the mean power outtake

$$\bar{P}_c = \frac{1}{2}E\big[\mathbf{F}_e^T(t)\mathbf{c}_c^{-1}\mathbf{F}_e(t)\big] - \frac{1}{4}\int_{-\infty}^{t} E\big[\mathbf{F}_e^T(t)\mathbf{c}_c^{-1}\mathbf{h}_{r\dot{v}}(t-\tau)\mathbf{c}_c^{-1}\mathbf{F}_e(\tau)\big]\,d\tau \qquad (70)$$

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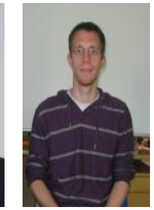
Department of Civil Engineering

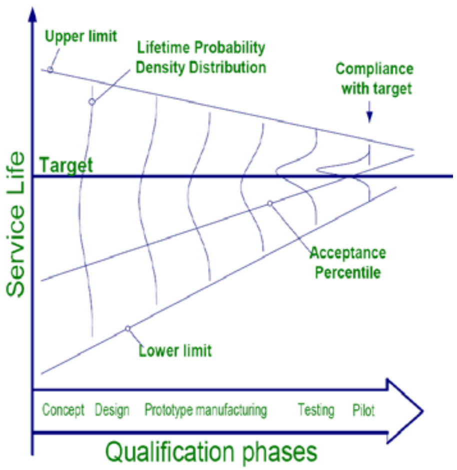
Reliability



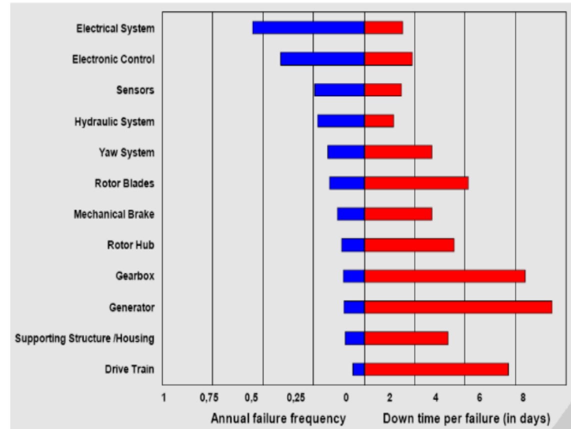
John Dalsgaard
Professor

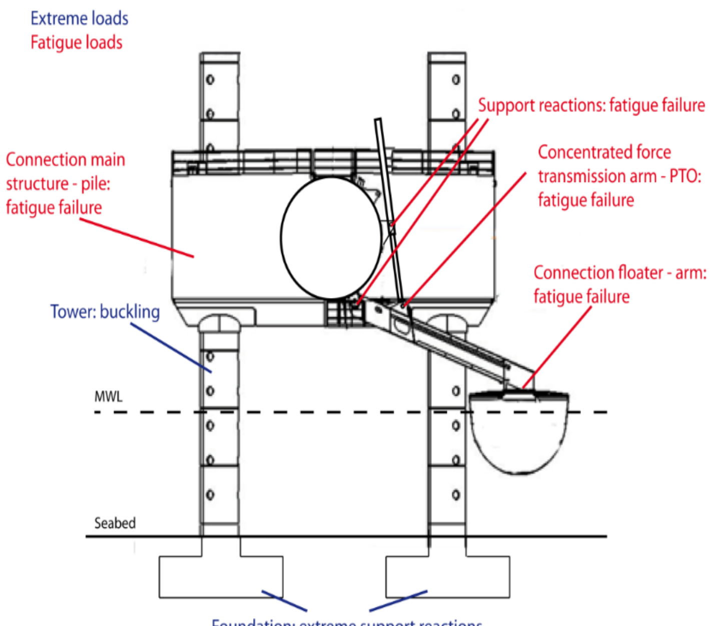
Simon Ambühl
PhD fellow

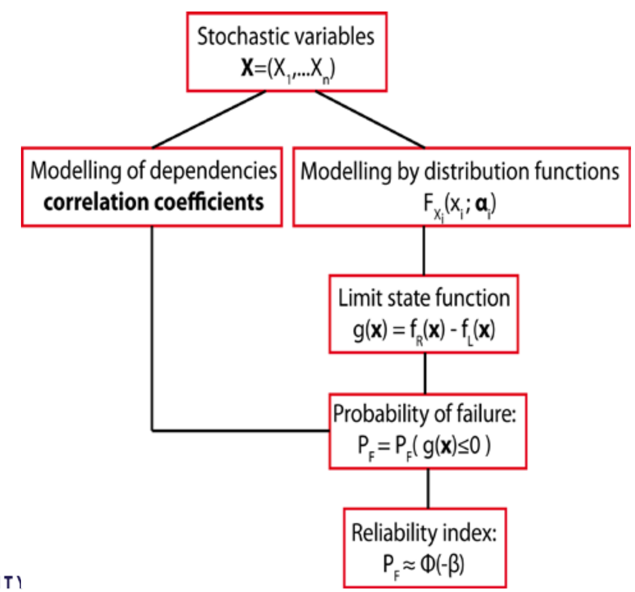
Lower the risk of failure and increasing the safety



WT Failure Rates and Downtimes (examples)







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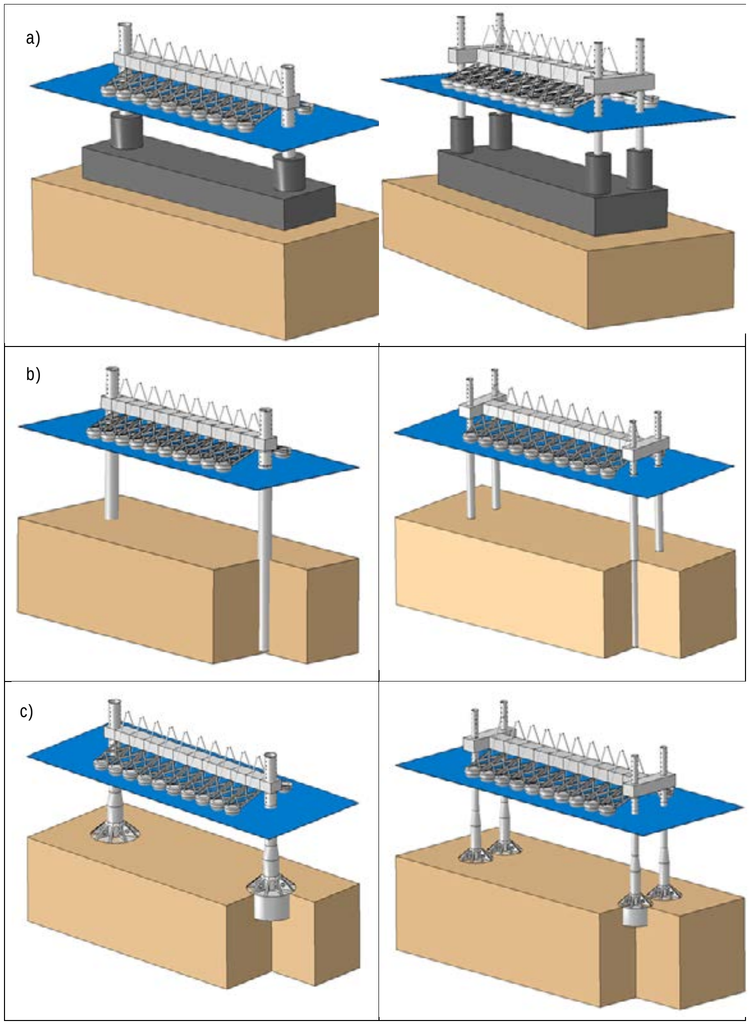
Foundation

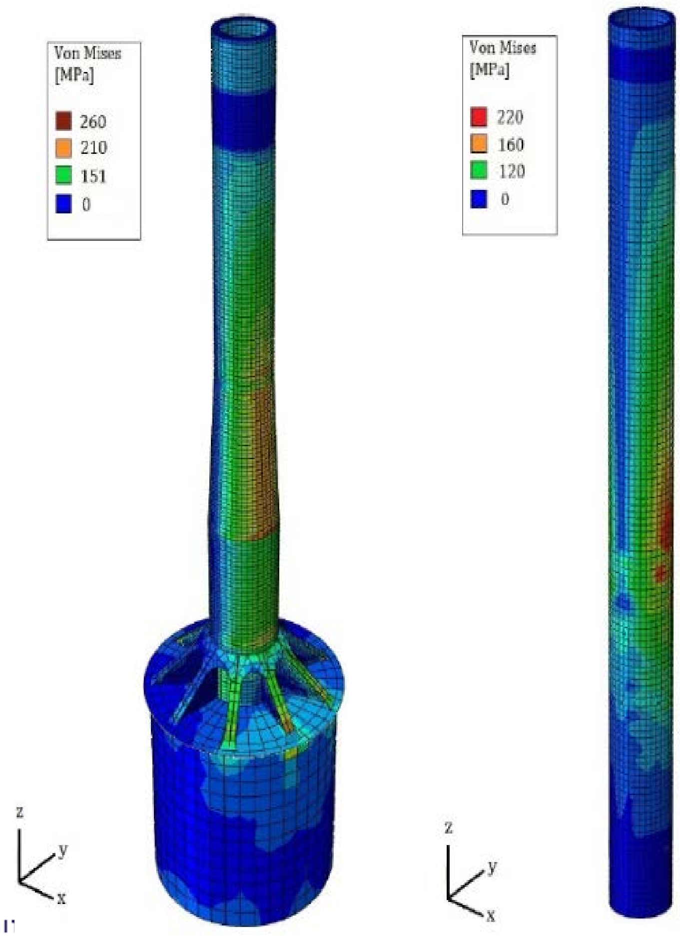
Lars Bo Ibsen
Professor

Evelina
Vaitkunaite
PhD fellow

Department of Civil Engineering

Lower the cost of foundation and installation





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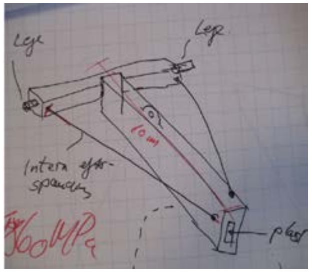
Structural design

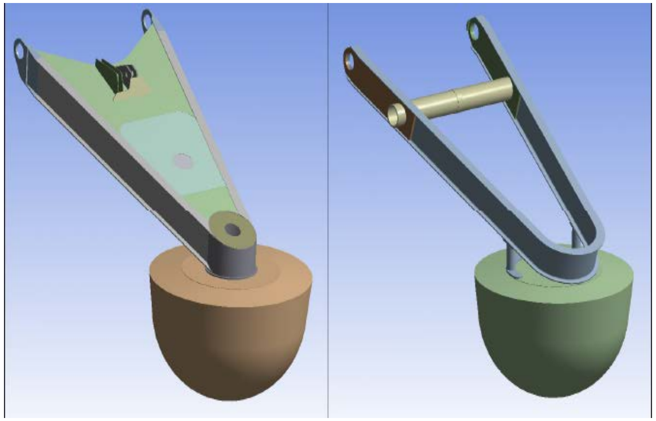
Lars Damkilde
Professor

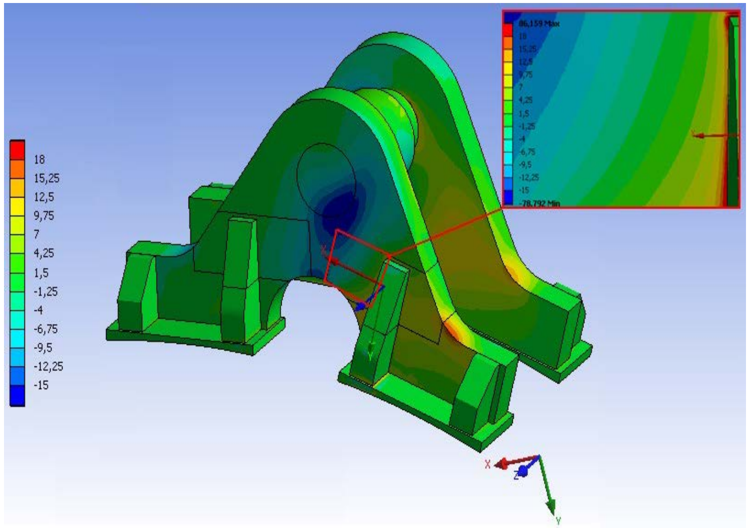
Michael Jepsen
Research Assistant

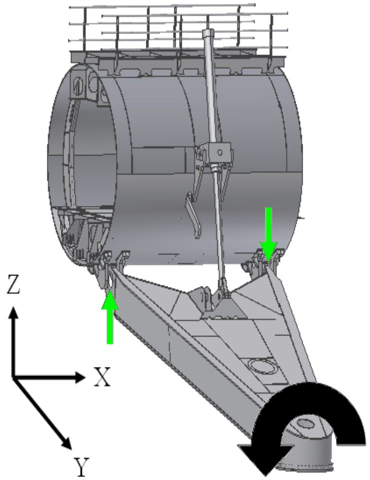
Department of Civil Engineering

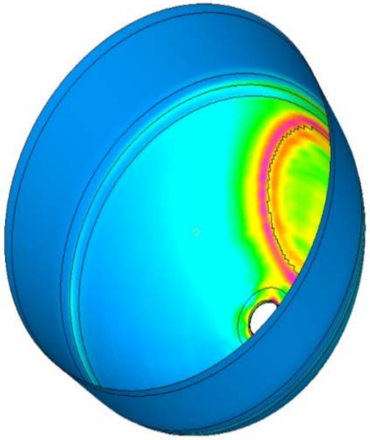
Lower the cost of the structure by optimizing the design











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Luis Pedro Esteves
Postdoc

Eigil Sørensen
Collaboration Partner

Department of Civil Engineering

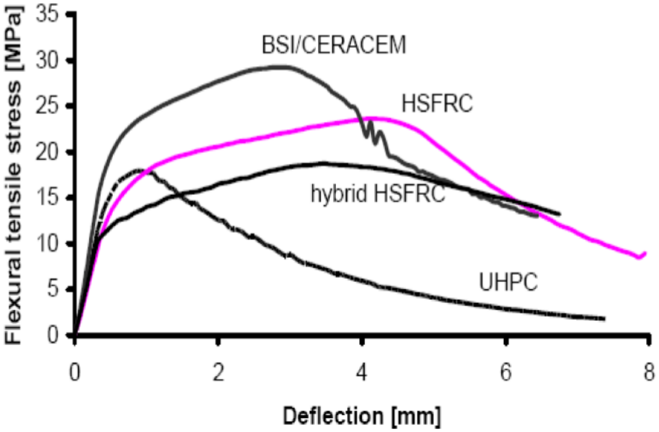
Lower the cost of the structure by using high strength concrete

BSI/CERACEM

HSFRC

Hybrid HSFRC

HSFRC	Trykstyrke [MPa]	Trækstyrke [MPa]
x_{middel}	146	20
σ	5	2
V	3%	9%



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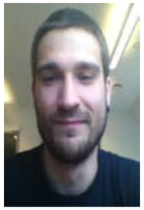
Loads, software


Thomas Lykke
Associate Professor


Morten Møller
PhD student

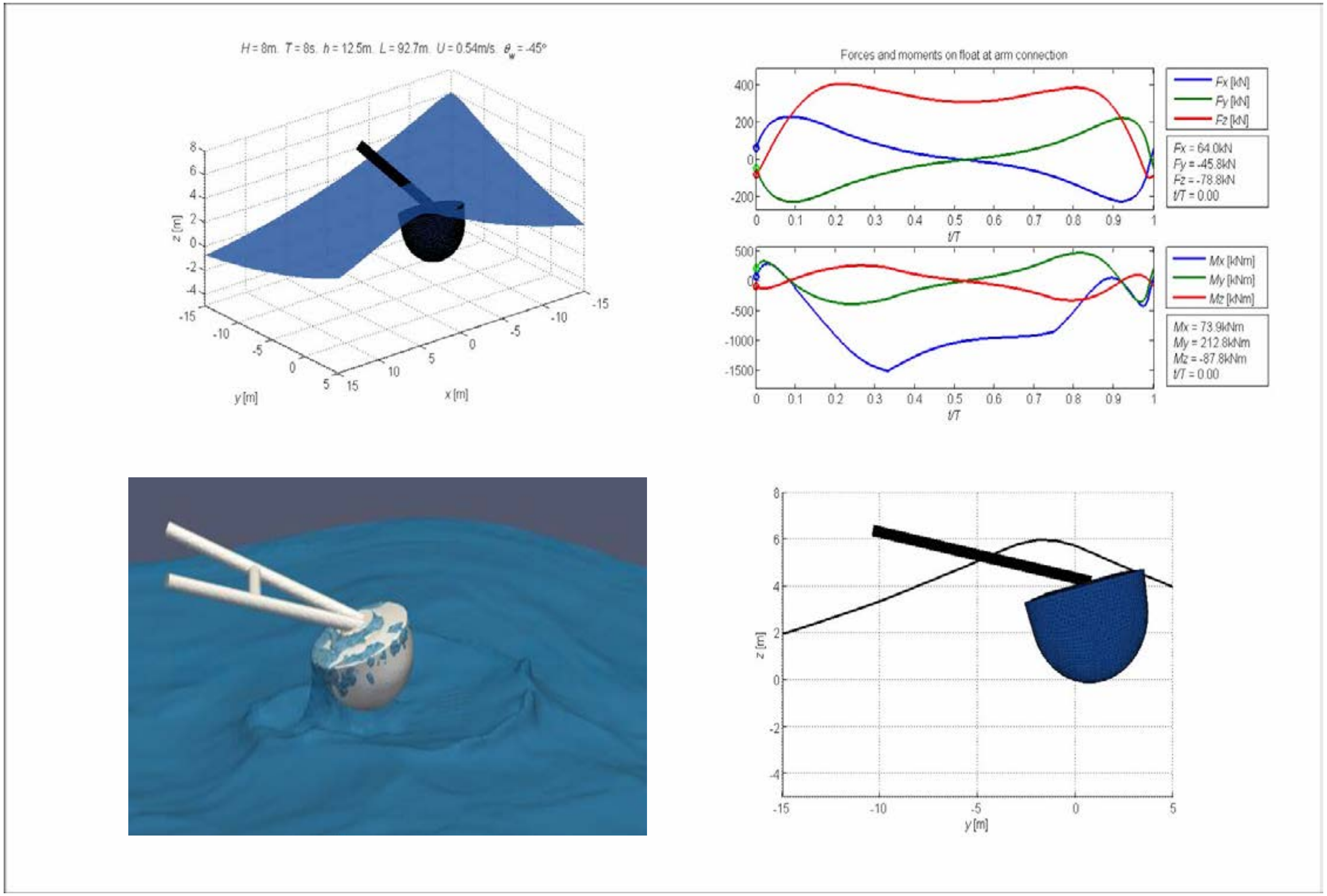

Francesco Ferri
Post doc


Jonas Bjerg
PhD student


Pau Mercadé Ruiz
PhD Fellow

Department of Civil Engineering

Loads scenarios for optimized design (lower the CoE)



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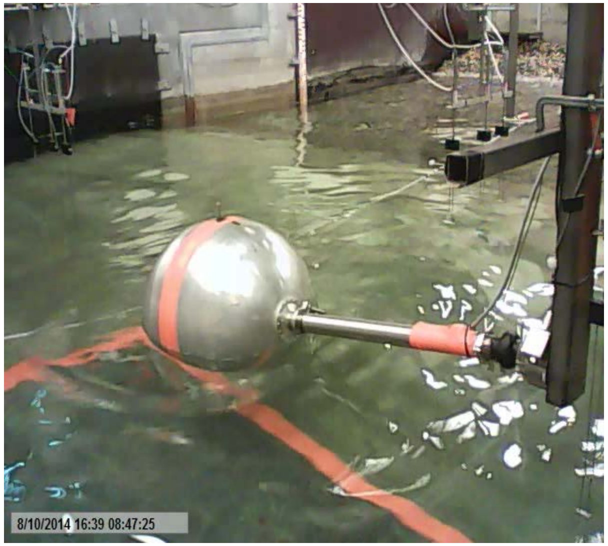
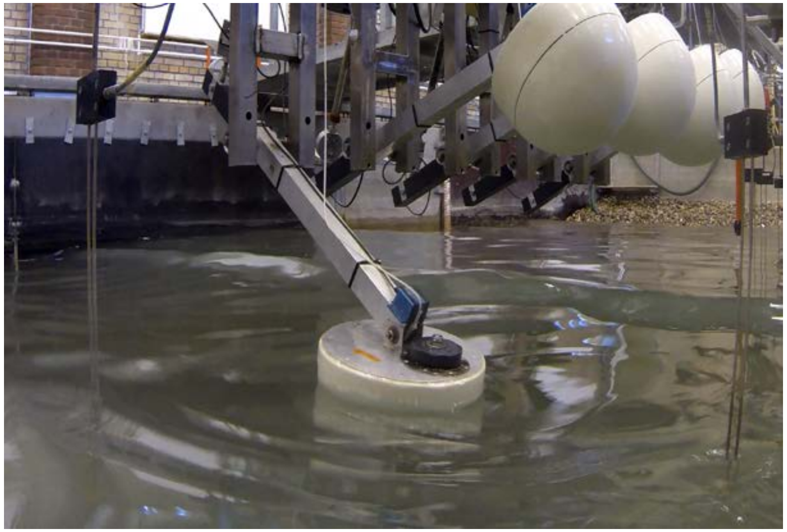
Facilities: Wave basins and channels

AAU has the Hydraulics and Coastal Engineering Laboratories which are extensively used by the Wave Energy Research Group for experimental testing of WECs.

During the last ten years several (more than 30) wave energy projects have been tested.

Two wave basins and three wave flumes are available.





http://www.civil.aau.dk/digitalAssets/101/101430_laboratoriet-for-hydraulik-og-havnebygning_uk.pdf

Facilities: Test site in Nissum Bredning

The group has been involved in instrumentation, test and assessment of energy production from 6 different devices tested in Nissum Bredning (intermediate scale, real sea).

Facilities: DanWEC in Hanstholm

The group has been involved in instrumentation, test and assessment of energy production at DanWEC (almost full-scale, real sea).

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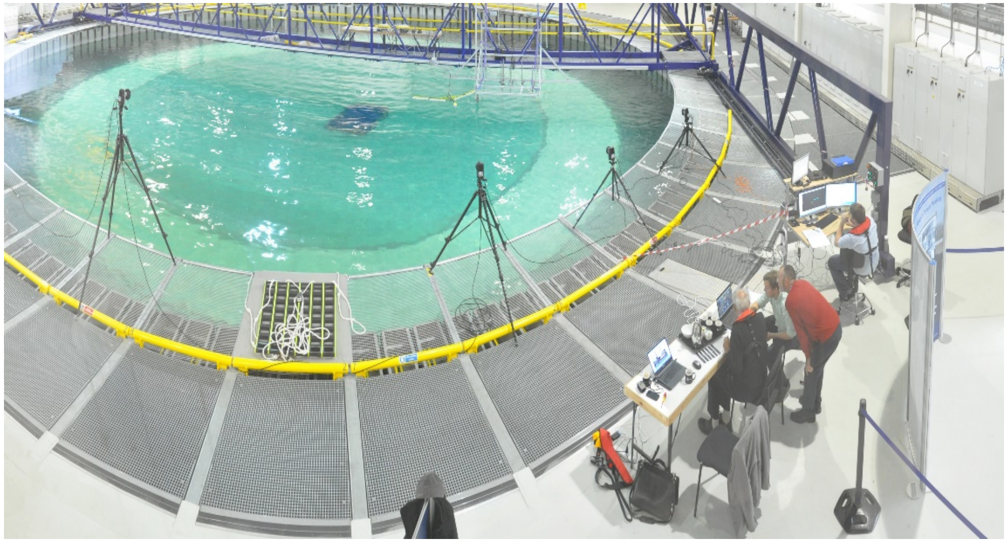
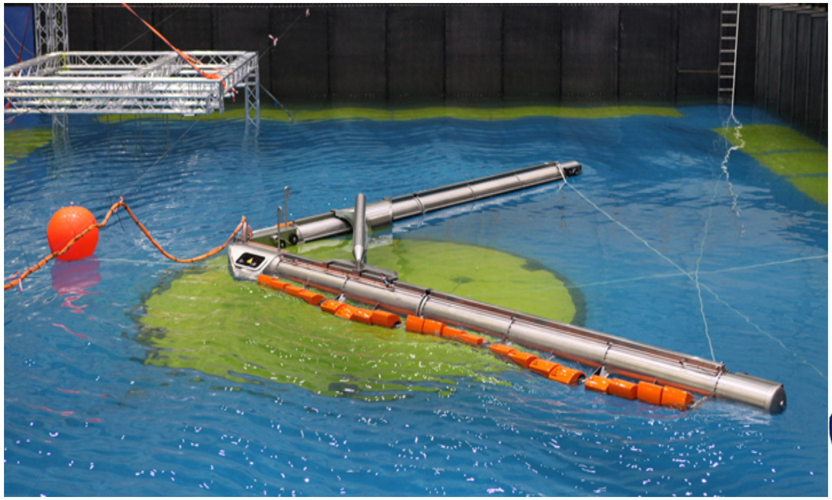
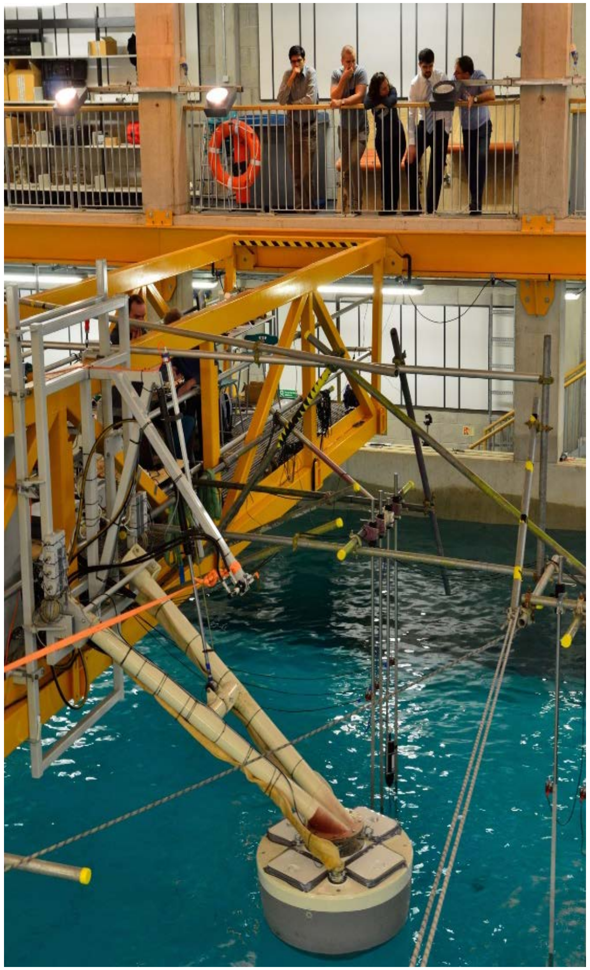
The group also participates in activities in other countries



FloWave in Edinburgh, http://www.flowavett.co.uk/



GTIMC in Santander
http://portal.meril.eu/converis-esf/publicweb/research_infrastructure/2226



COAST in Plymouth
https://web-dr.tis.plymouth.ac.uk/research/institutes/marine-institute/coast-laboratory

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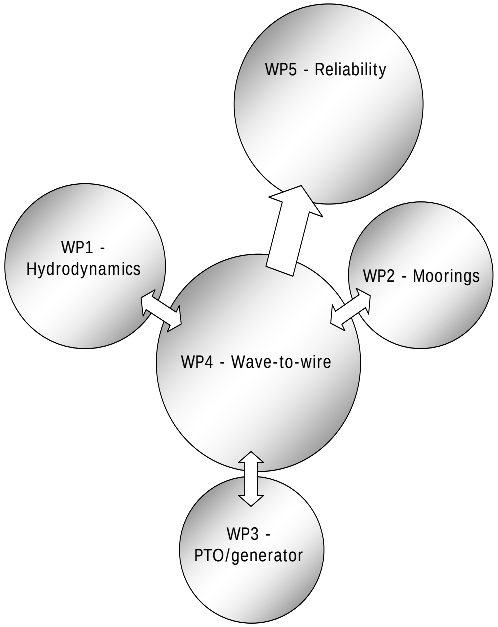
Researcher training in wave energy at Aalborg University

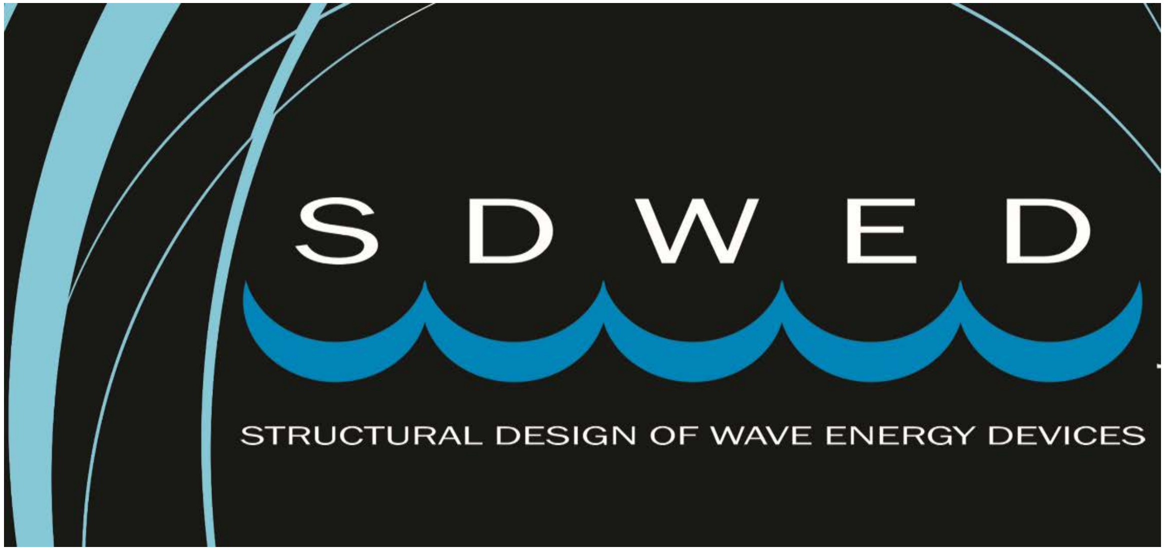
Aalborg University has a long tradition of offering both PhD and Master level courses related to wave energy.

The next PhD course is taking part in the two weeks before the EWTEC 2015 conference in Nantes: http://www.ewtec.org/ewtec2015/wec-course/

We are also organizing tours and seminars to a wide range of people and organizations.

The SDWED project





SDWED was granted by the **Danish Council for Strategic Research**

The 5 year project is now finished (2010-2014)

There are a lot of outcomes of the project:
- Reports, publication and software is publicly available for download via http://www.sdwed.civil.aau.dk/
- New initiatives and projects have spun out of the project (next slides)

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Ongoing projects in the Wave Energy Research Group

- **Optimal Design Tools for Ocean Energy Arrays (DTOcean)**
  EU FP7 Theme: ENERGY.2013.2.6.1 (#608597)
- **Standardization related to wave energy DS S-614 and IEC TC 114**
  EUDP 2008-I, 63036-0020 and 2009-I, 64036-0004 and ForskEL 12180
- **Cost Effective Foundation and Installation of Wave Energy converters**
  ForskEL 10796
- **Digital Hydraulic Power Take Off for Wave Energy**
  ForskEl 12155
- **FLOAT2 – New Flexural UHPC Application for Wave Converters 2**
  ForskEL 10754
- **WaveSpring for enhancing wave energy absorption**
  EUDP 2014-I, 64014-0156
- **Mooring solutions for large wave energy converters**
  EUDP 2014-I, 64014-0139
- **Capacity credit of wave and solar energy**
  ForskEL12134
- **Gyro electric energy converter unit for wave energy**
  EUDP, 64014-0129

- ... There are some more (maybe 5-10)...

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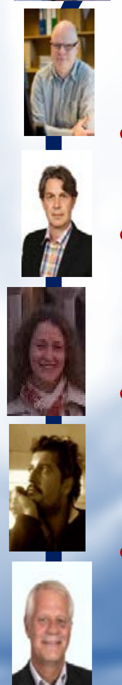
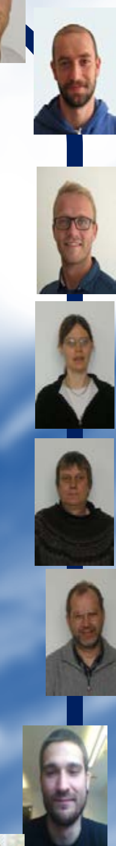
In summary Aalborg University has:



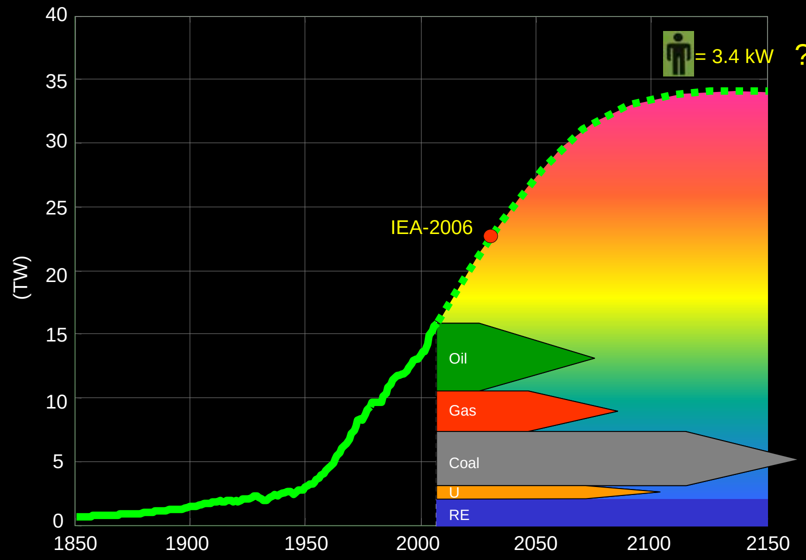


- **many competences useful for development of WECs,**
- **excellent facilities and highly experienced personnel in testing of WECs,**
- **teaching classes and research training to educate the future engineers to design WECs,**
- **a long list of successful previous and current WEC projects, and many new project applications are in the pipeline.**

Why wave energy?

As with other renewable energy sources:

- Climate change (CO_2 problem)
- The finite ressource of fussil fuels (oil, coal, gas, uranium)
- Security of supply – political stability
- Jobs



Never say never
1974, Risø report:

”Vindenergi vil aldrig kunne bidrage væsentligt til elproduktionen i Danmark”

”Vindenergi vil aldrig blive rentabelt”

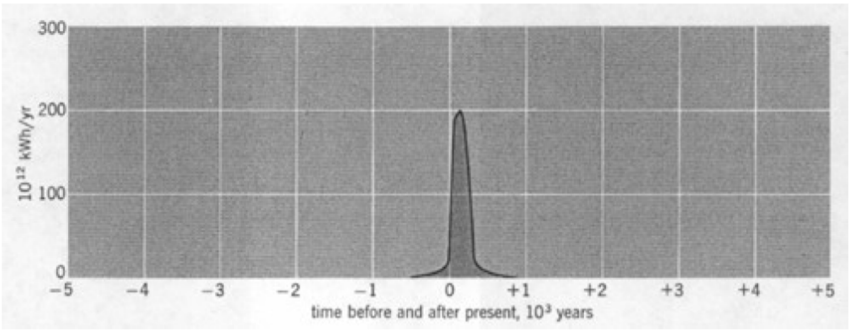
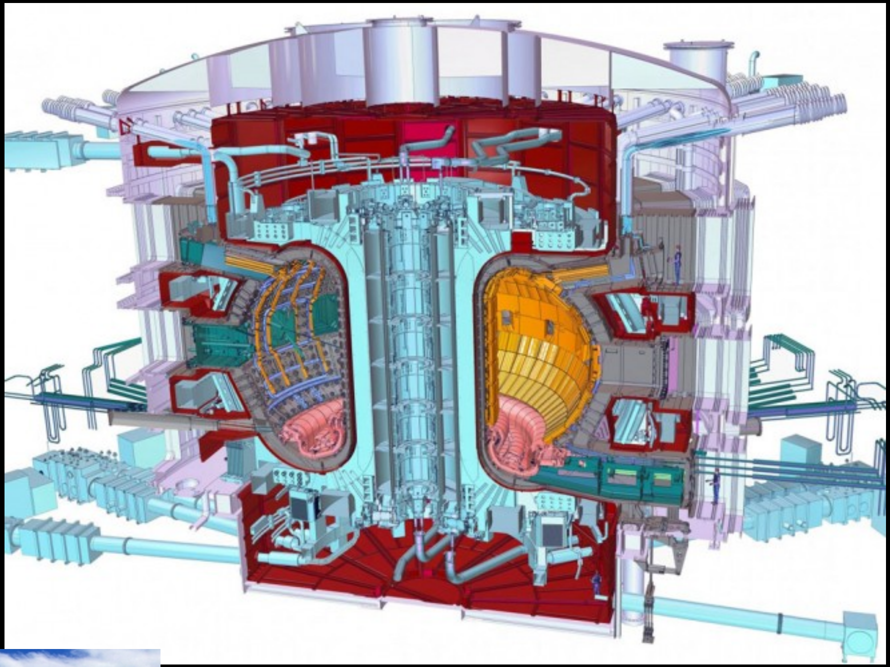


Fig. 19: The epoch of fossil-fuel exploitation as it appears on a time scale of human history ranging from 5000 years ago to 5000 years into the future. (From Hubbert, op. cit., 1974)

What are the options?

- Nuclear Fission/Fusion
- Renewable energy



http://www.ted.com/talks/amory_lovins_a_50_year_plan_for_energy.html

Cost of Energy (in Denmark)

ENERGY TYPE	€/MWh
Floating Offshore Wind	400-1500
Wave Energy	~750
Photovoltage	~125
Offshore Wind	75-125
Onshore Wind	40-75
Coal	30-45

30% of our electricity comes from wind.
Why ?

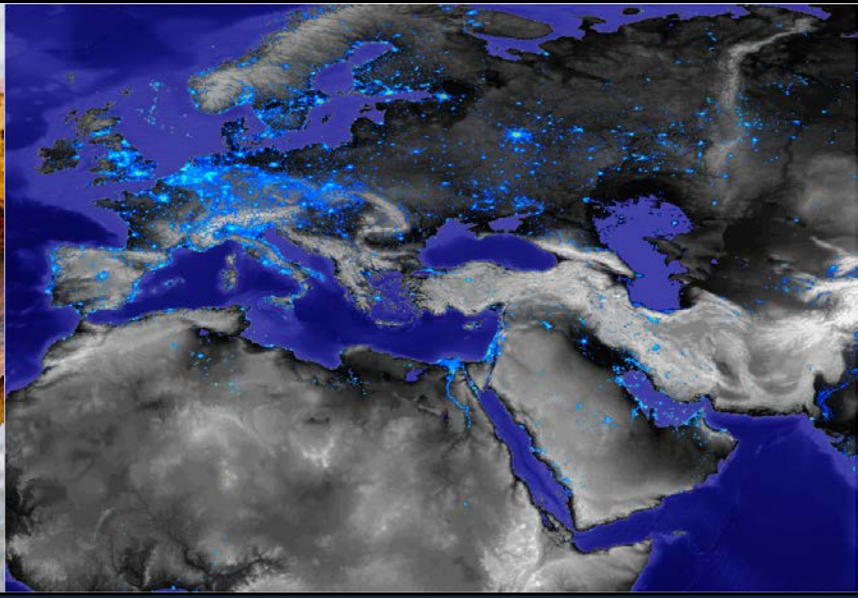
We are interested in Wave Energy.
Why ?

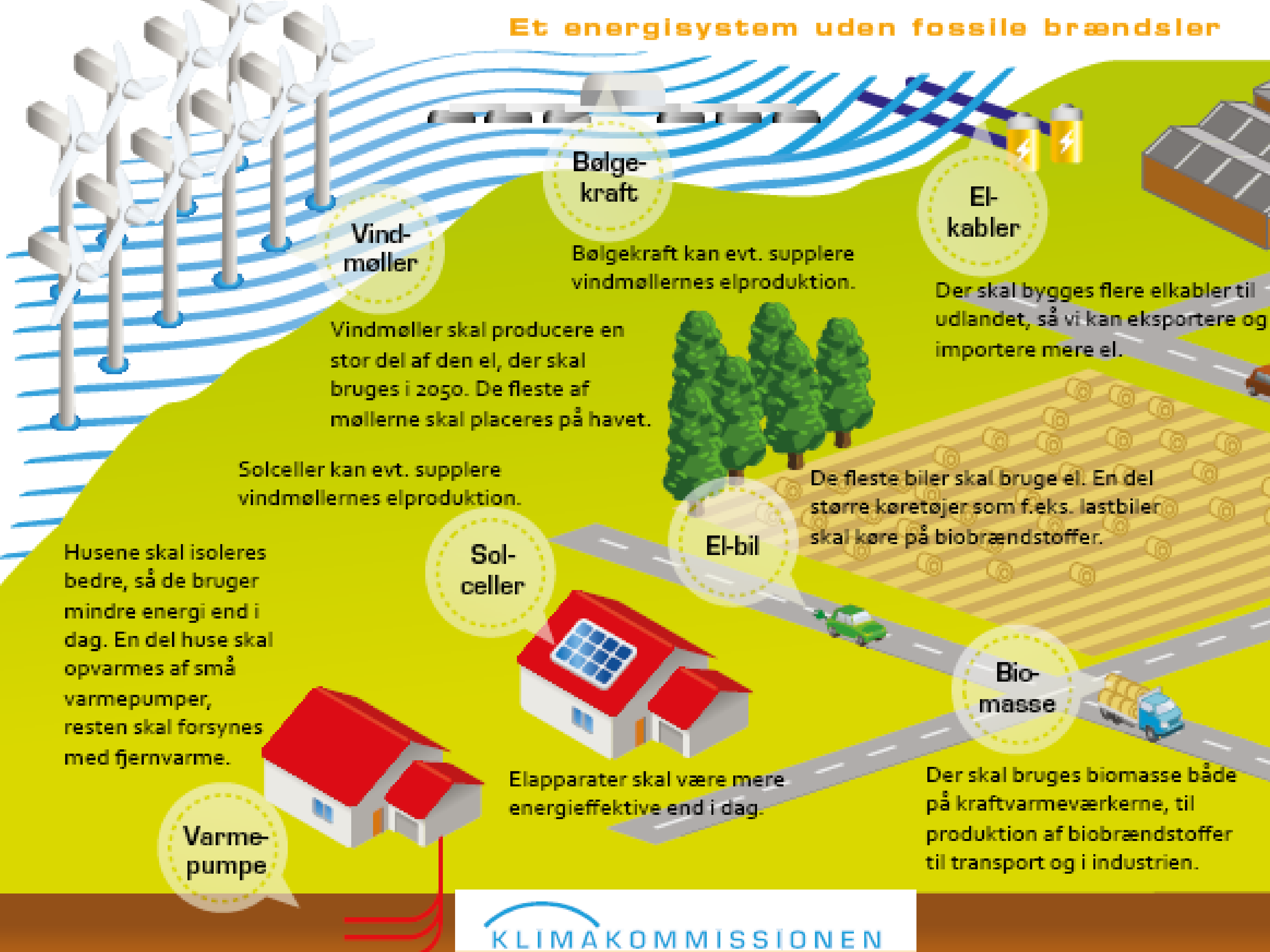
Cost of Energy important but not essential

Energy policy is driven by politics

There is a growing demand for clean energy, the main drivers are not just Jobs, Environment, Global Warming
Nations wants to secure energy supply





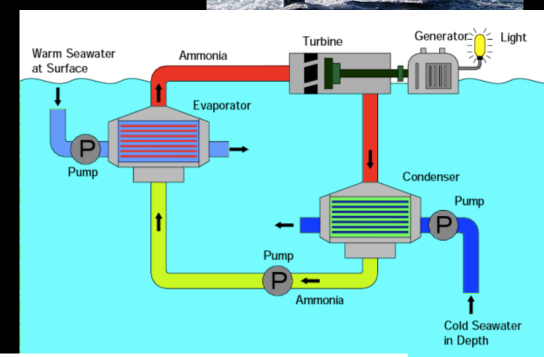

Et energisystem uden fossile brændsler
Bølge-kraft
Bølgekraft kan evt. supplere vindmøllernes elproduktion.
El-kabler
Der skal bygges flere elkabler til udlandet, så vi kan eksportere og importere mere el.
Vind-møller
Vindmøller skal producere en stor del af den el, der skal bruges i 2050. De fleste af møllerne skal placeres på havet.
Solceller kan evt. supplere vindmøllernes elproduktion.
De fleste biler skal bruge el. En del større køretøjer som f.eks. lastbiler skal køre på biobrændstoffer.
El-bil
Sol-celler
Husene skal isoleres bedre, så de bruger mindre energi end i dag. En del huse skal opvarmes af små varmepumper, resten skal forsynes med fjernvarme.
Bio-masse
Elapparater skal være mere energieffektive end i dag.
Der skal bruges biomasse både på kraftvarmeværkerne, til produktion af biobrændstoffer til transport og i industrien.
Varme-pumpe
KLIMAKOMMISSIONEN

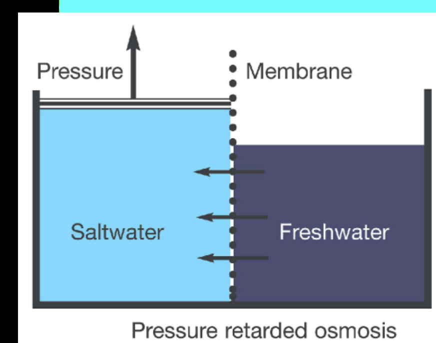
Potential ocean energy worldwide

Wave – 3 (1-10) TW (3×10^{12} W)
Ocean currents – 0,05 TW
Tidal currents – 0,2 TW
Temperature gradient – 3,8 TW
Osmose / salinity – 2,3 TW

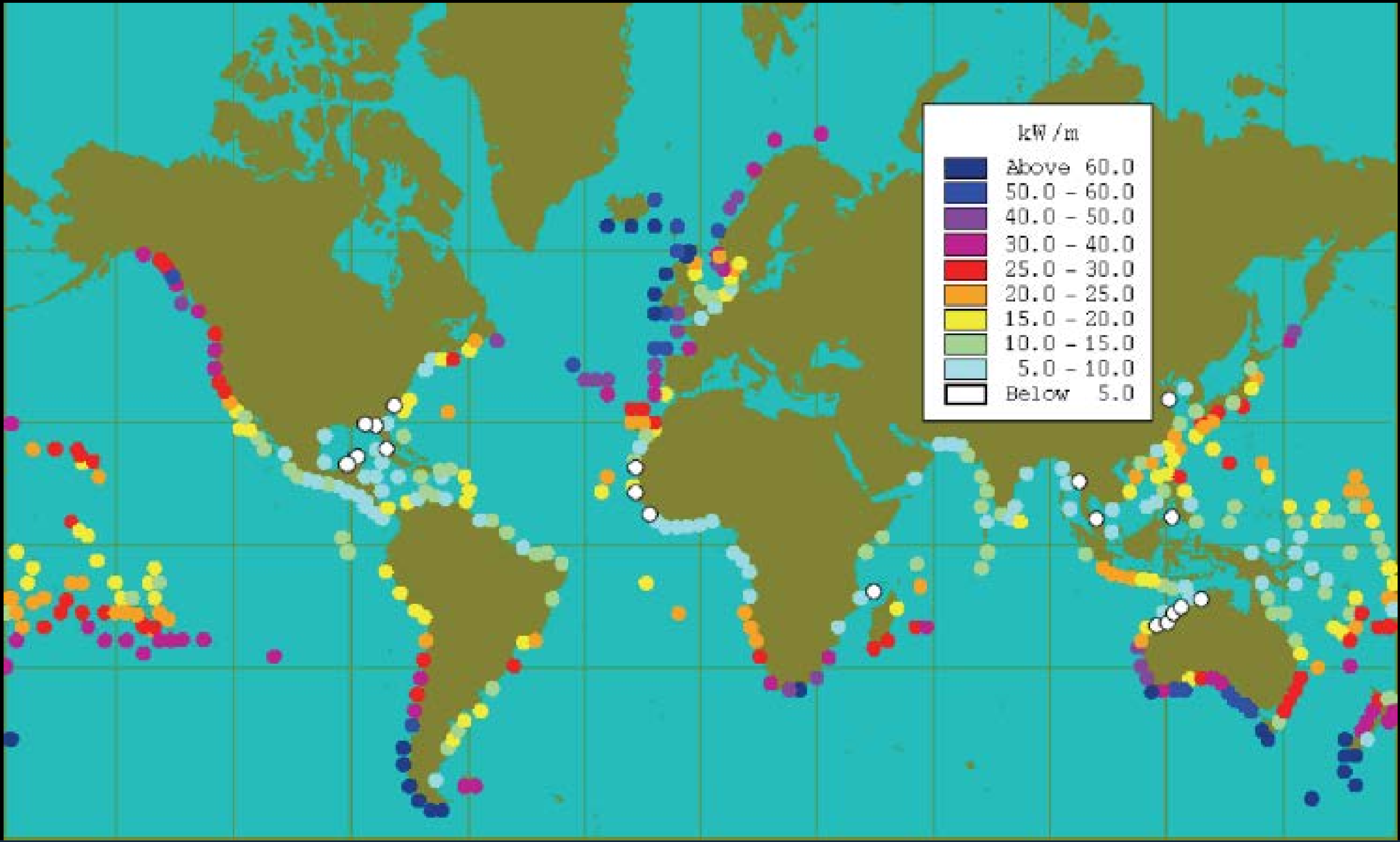
Global energy needs~ 15 TW
(140×10^{12} kWh/year)
(2005)

Note: Global solar energy: 120.000 TW
- ca. 8.000 times world consumption!





The Wave Energy Ressource is Enormous.
~ 20 % of Worlds Energy Needs



Potential wave energy in Europe

Denmark's electricity consumption: 3,7 GW

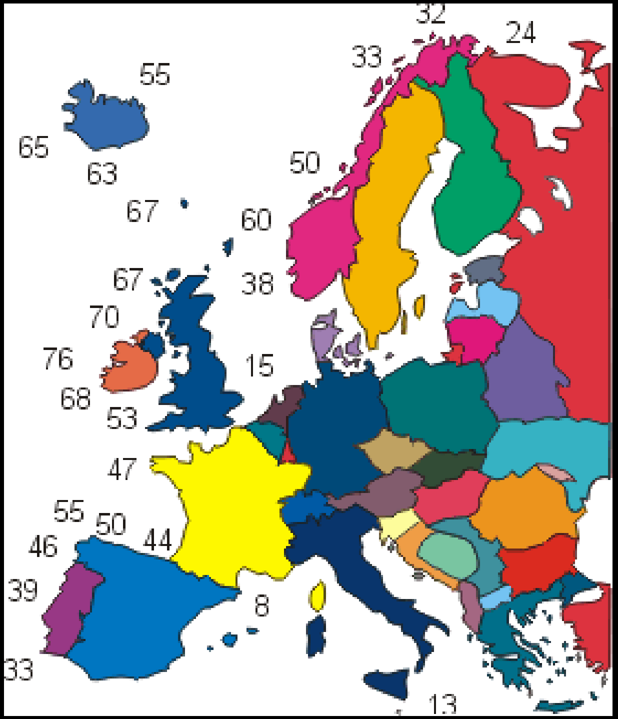
Danish West coast (offshore):

- Up to 25 MW/km
- averagely 16 MW/km
- Around 150 km from the coast ~ 2,4 GW

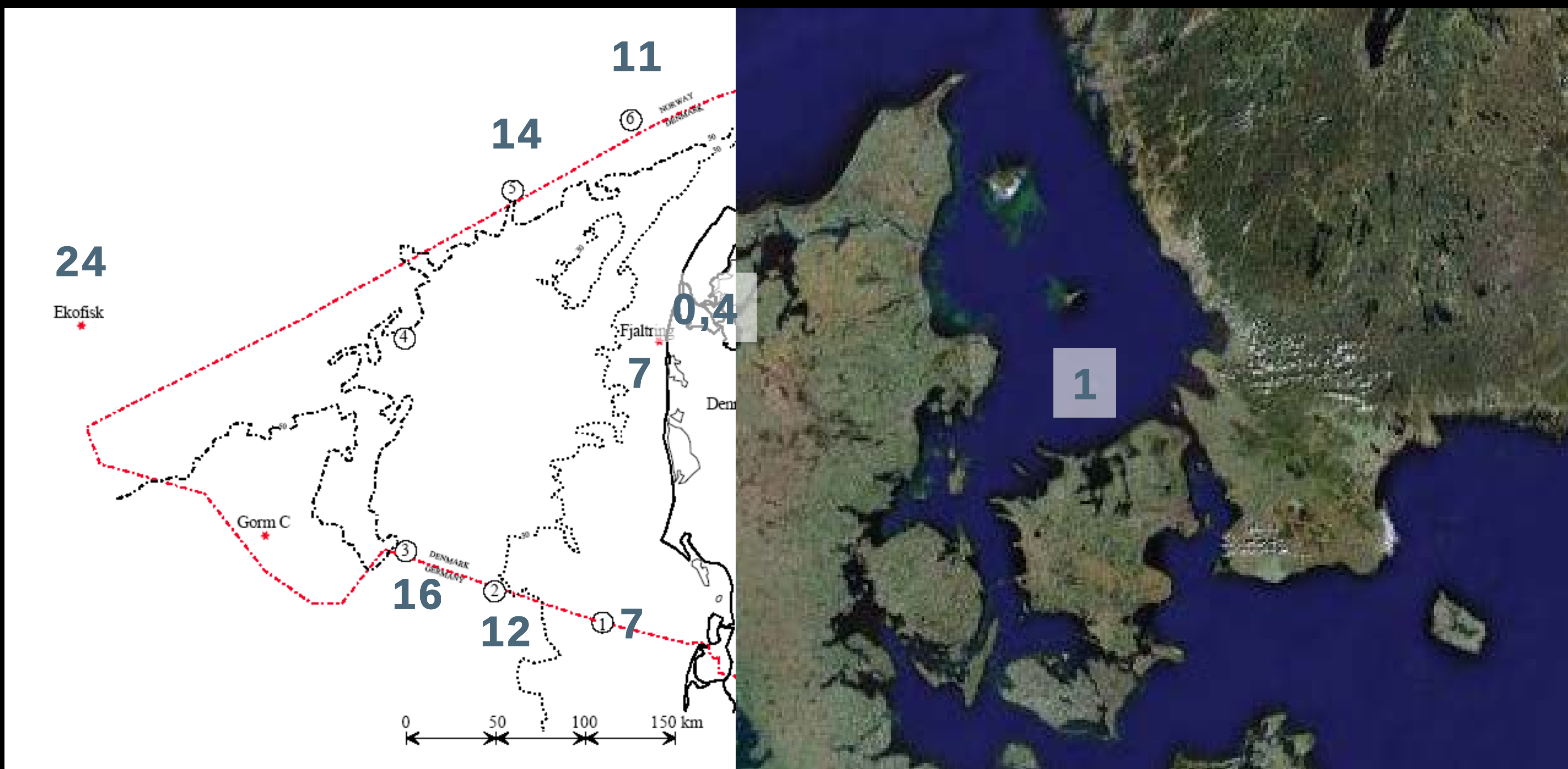
In the European Atlantic/North Sea coasts: 25 - 75 MW/km

Mediterranean sea: 4 - 11 MW/km

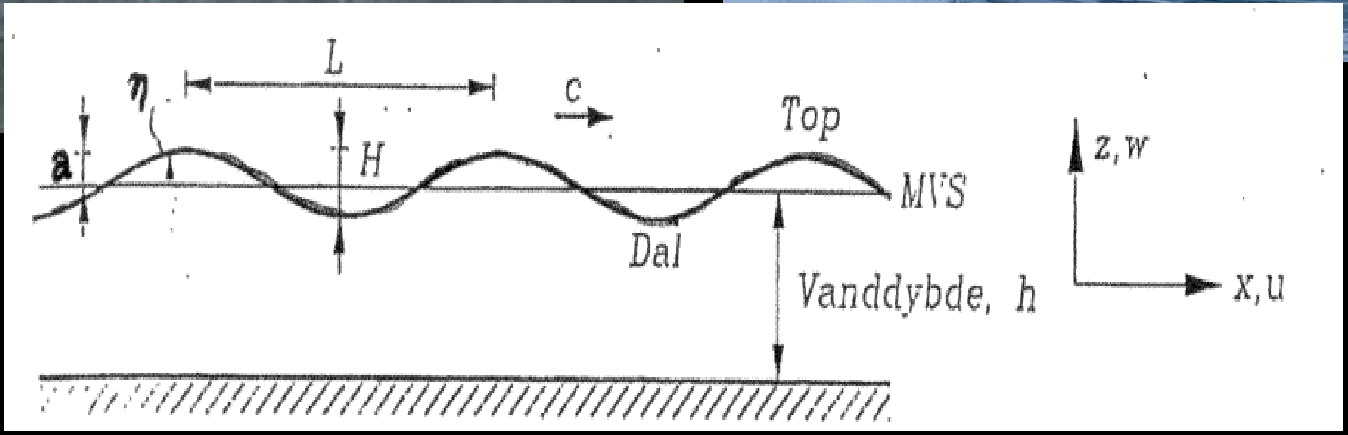
Total potential on European coasts: ca. 320 GW



Potential wave energy in Denmark

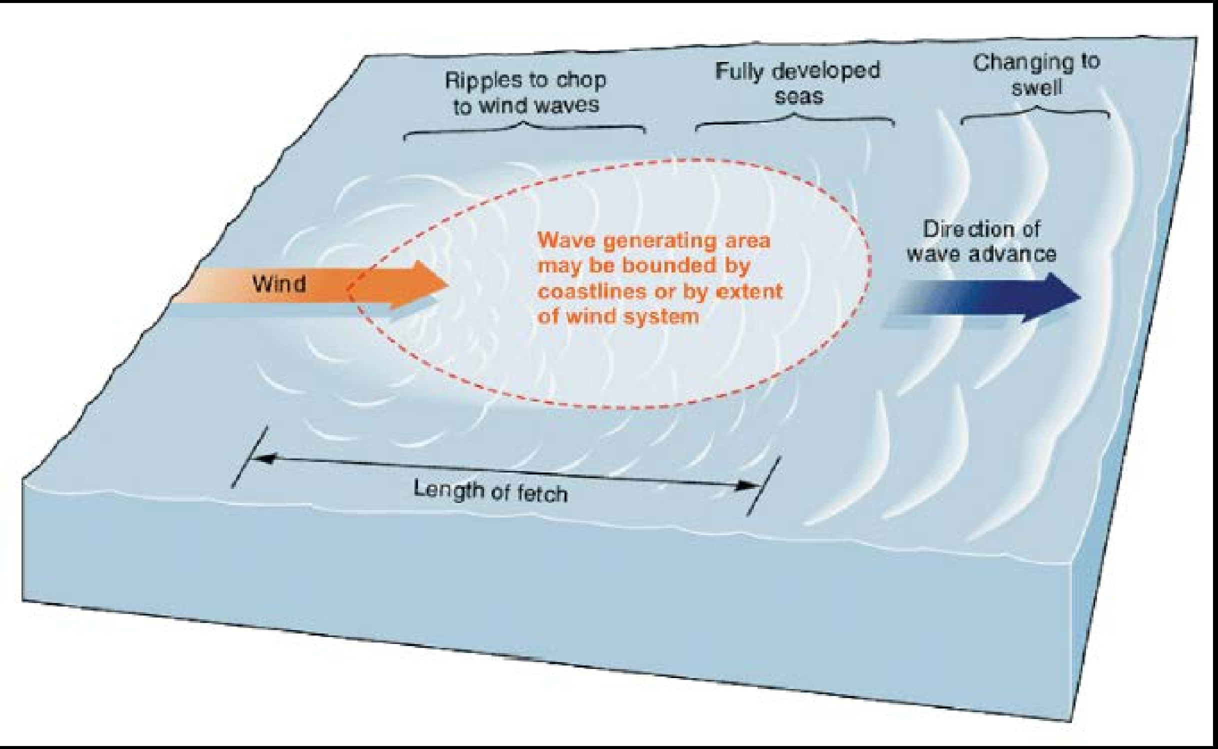


What are ocean waves?

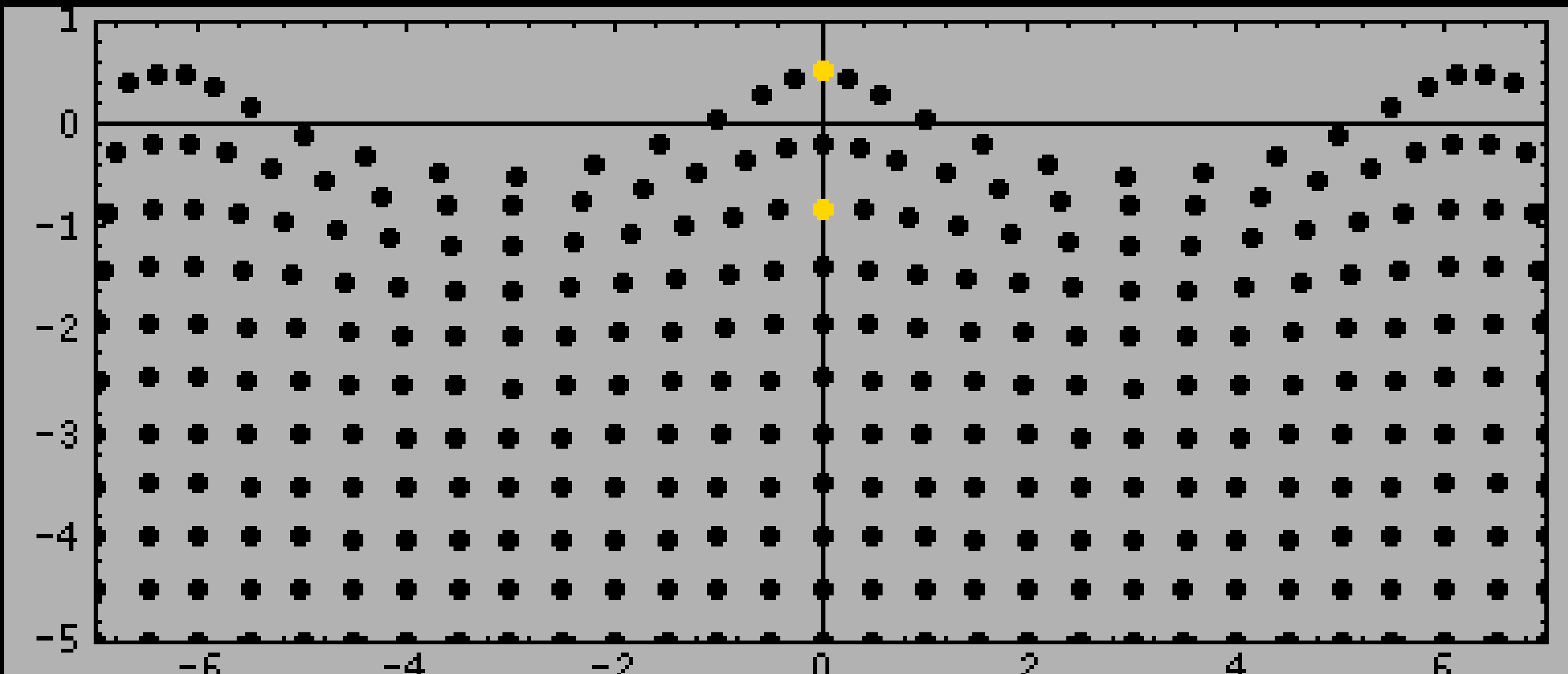


Where do they come from?

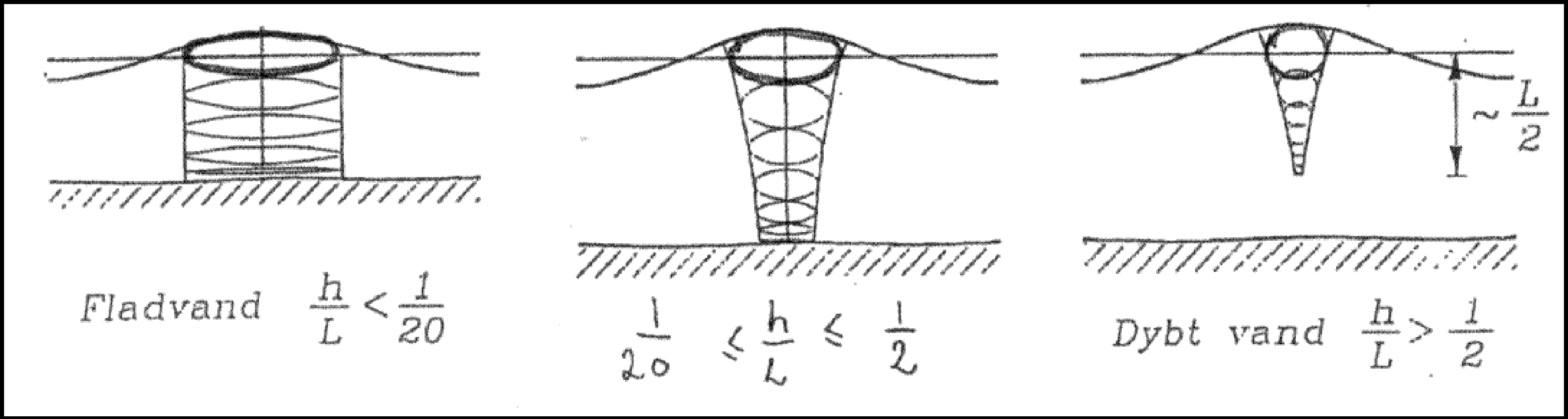
- Uneven heating of the earth by the sun drives wind.
- Wind drives the waves



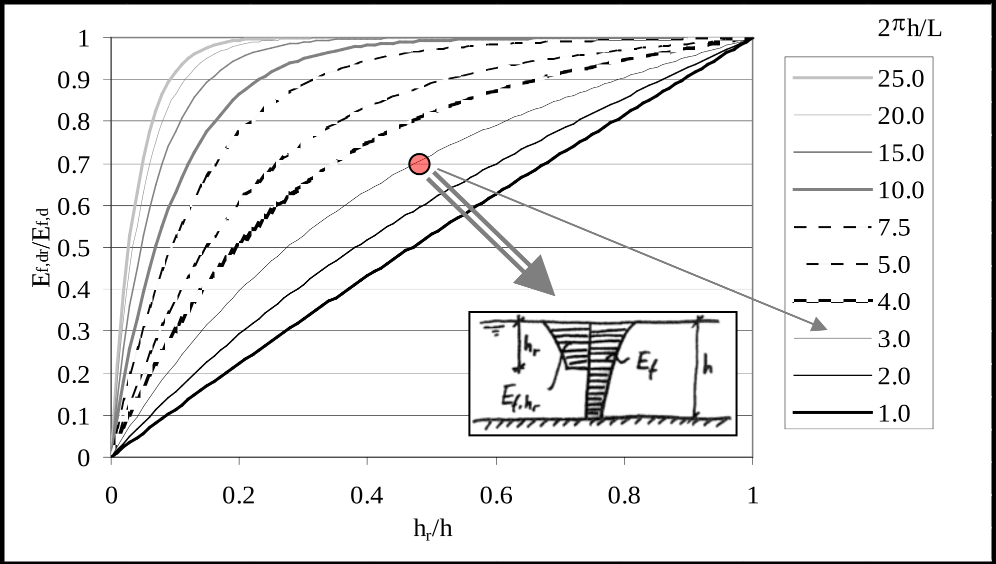
Waves move energy – not water!



Wave particle motions



Depth dependency of energy content



Energy content of waves

Potentiel energy [J/m²]: $$E_{pot} = \tfrac{1}{16}\rho g H^2$$

Kinetic energy [J/m²]: $$E_{kin} = \tfrac{1}{16}\rho g H^2$$

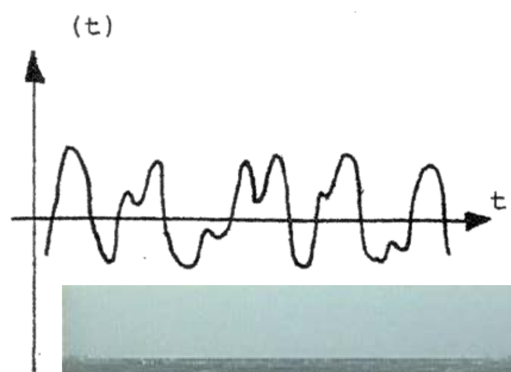
Total energy [J/m²]: $$E = \tfrac{1}{8}\rho g H^2$$

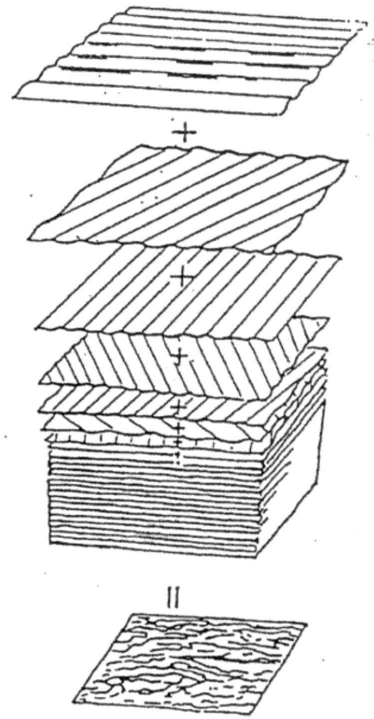
Energy flux (power) [W/m]: $$P_w = \int_{-h}^{0} p^{+} u \, dz$$

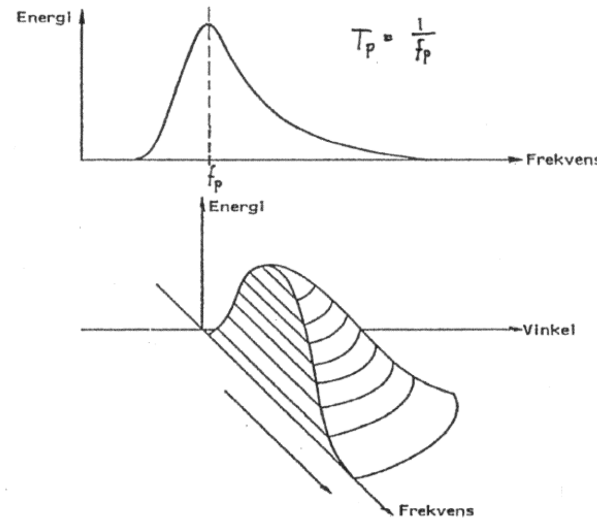
$$= \tfrac{1}{16}\rho g H^2 \frac{L}{T}\left(1 + \frac{2\frac{2\pi}{L}h}{\sinh\left(2\frac{2\pi}{L}h\right)}\right)$$

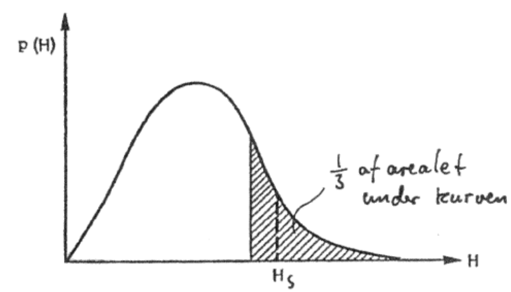
Irregular waves

$$P^u_w = \frac{\rho g^2}{64\pi} H_s^2 T_E$$









An example

IDA2030:

- Wave power delivers 5 % of DK electricity consumption (35 TWh/y) through 500 MW installed WEC capacity.
- Assumptions:
  - 40 % load factor
  - 10 % overall efficiency (farm layout)
  - 15 MW/km average available wave power
- Result:
  - Use of 133 km


Ressourceopgørelse for bølgekraft i Danmark

J. P. Kofoed

Carried out under contract for:

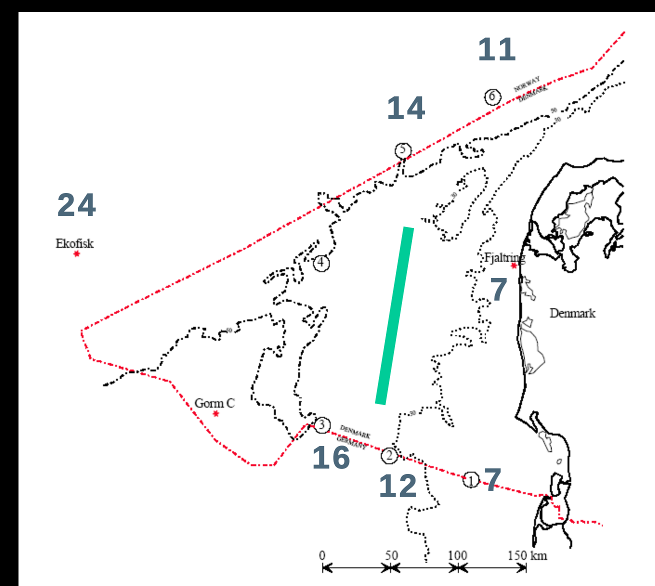
Klimakommissionen

KLIMAKOMMISSIONEN

AALBORG UNIVERSITY

Department of Civil Engineering

DCE Contract Report No. XX



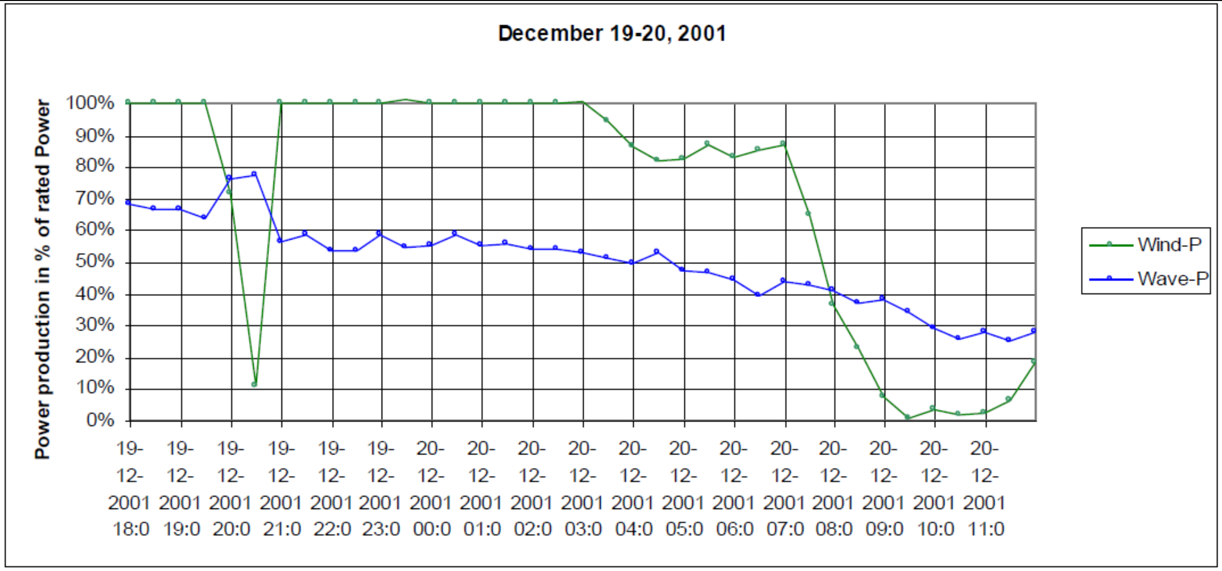
Why Wave Energy?

The wave energy resource is:

- Concentrated
- Predictable
- Available
- Close to consumption points

Wave energy vs. wind energy

- Energy from waves more smooth in medium time scale (15-30 min), and phase shifted compared to wind
- More accurate forecasting of waves than wind.
- Often higher energy production from a given area from waves compared to wind (location dependentt)
- Less visual intrusion from wave than wind.



Wave Energy has the potential to contribute significantly to the worlds energy production

but…

How do we develop the right technologies?

The Danish Wave Energy Program 1998 - 2002

A quite "wide" development strategy

Projects carried out during a 4 years period:

- 40 – 50 inital phase, simple model testing (Phase 1)
- ~10 further R&D (Phase 2)
- 1 real sea testing (Phase 3)

Roughly half of all of the projects were carried at DCE, AAU

Total budget for the program was €5.4 mill

Staged development

Classification into 4 phases:

- Each phase should provide specific valuable information to inventor and investors, before going to the next step
- Avoid spending too much resources before having a reliable estimate on the concepts potential

Definition of phases:

- Phase 1: Proof of Concept
- Phase 2: Detailed investigations
- Phase 3: Real sea testing, at smaller scale
- Phase 4: Demonstration in half to full scale

Laboratory testing in wave basin/flume

Focus on:

- Wave induced loadings
- Wave induced motions
- Power production

Phase 1:

- Rough estimates of power production, based on simple measurements. Accuracy level: +/-20 %
- Qualitative observations of behavior in ”large waves” / extreme conditions

Phase 2:

- More detailed measurements of power production, load optimization, optimization of geometrical configuration etc. Accuracy level: +/-5 %
- Measurements of loadings and motions in extreme conditions

Real sea testing

Focus on:

- Wave induced loadings
- Wave induced motions
- Power production
- Advanced control

Phase 3 – real sea testing:

- Detailed measurements of power production on “real” PTO system. Corrections for extra losses due to scaling.
- Testing of advanced control strategies.
- Measuring loadings/strains in the structure.
- Calibration/verification of numerical models of concept.

Real sea testing

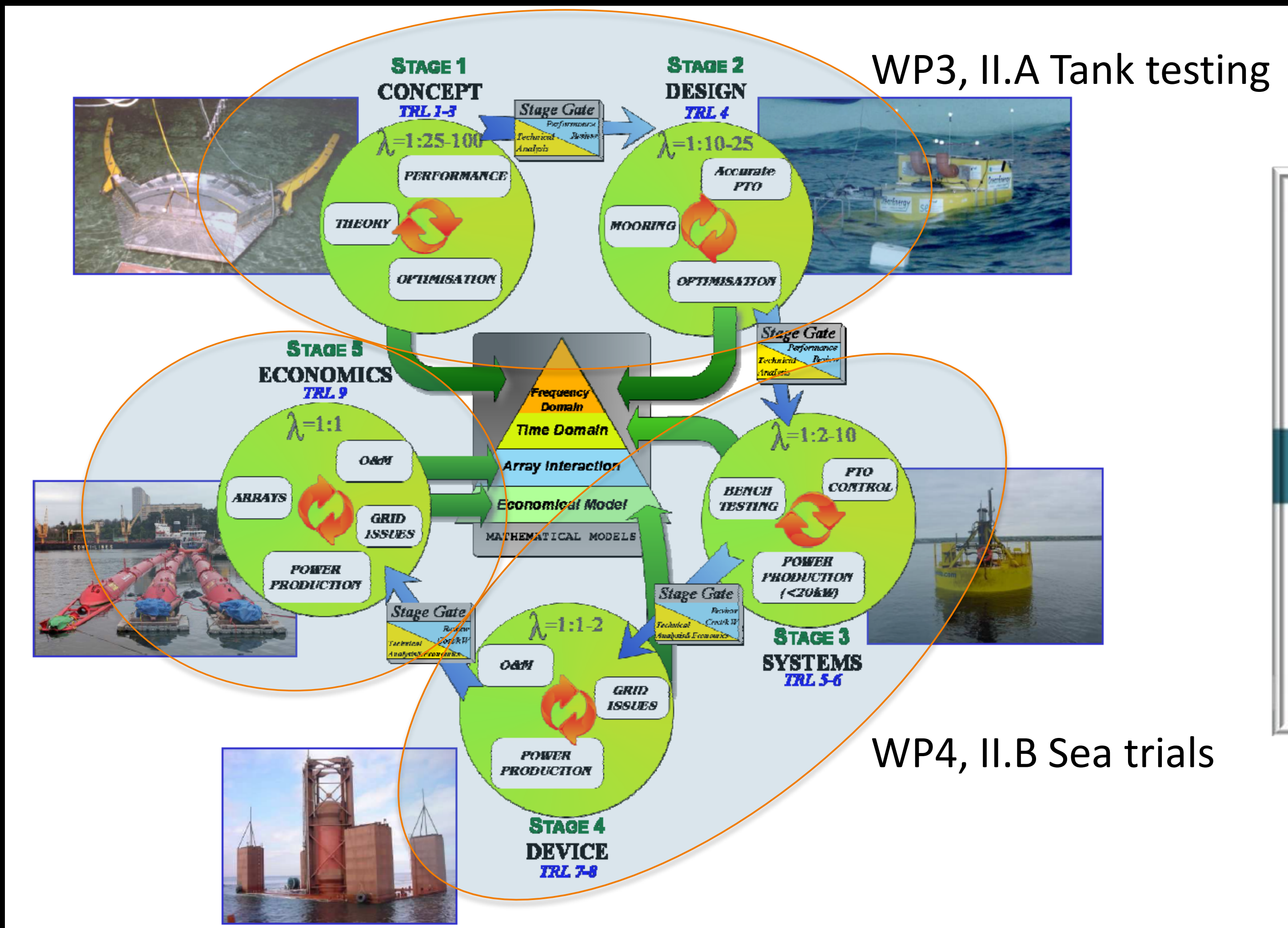
Focus on:

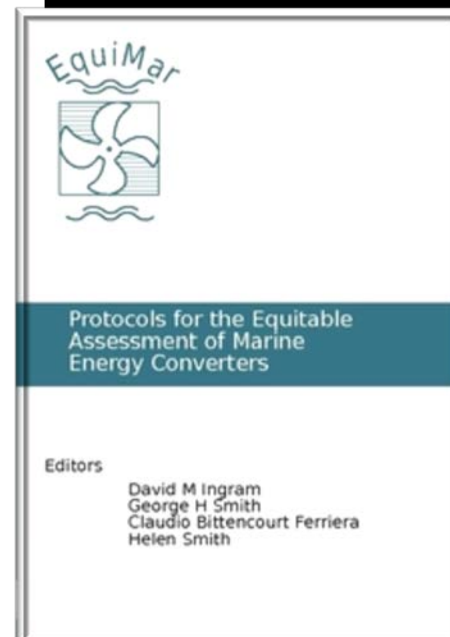
- Wave induced loadings
- Wave induced motions
- Power production
- Advanced control
- Economical performance

Phase 4 – demonstration:

- Economical demonstration
- Component testing
- Operational experience
- Maintenance

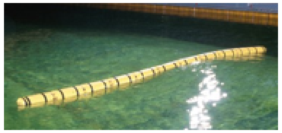
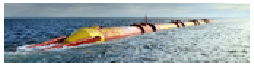
EquiMar





Print-to-order hardcopy of Final protocols: http://www.lulu.com/product/paperback/protocols-for-the-equitable-assessment-of-marine-energy-converters/15675151

5 stages development - example

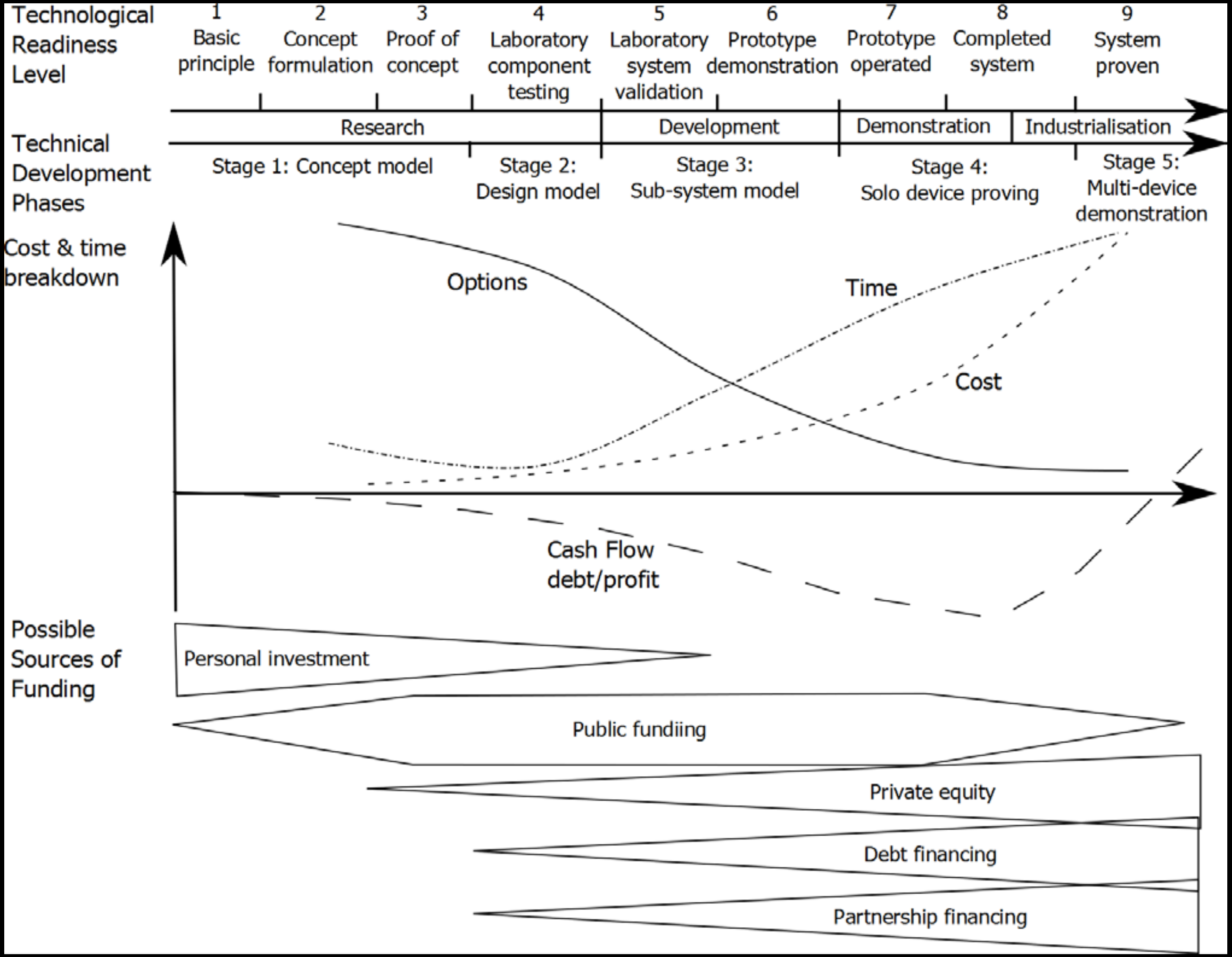
	Stage 1: Concept model	Stage 2: Design model	Stage 3: functional model	Stage 4: WEC prototype	Stage 5: Array demonstration
Illustration				 	
Scale	1:20 - 1:100	1:10 - 1:50	1:3 - 1:10	1:1 - 1:3	1:1
Location	Laboratory	Laboratory	Laboratory / Benign site	Open seas	Open seas
Model / Prototype characteristics	- Idealized setup - Load-adaptable PTO - Adaptable design variables	- Final design - Representative characteristics - Simulated PTO	- Full fabrication - True PTO and - Electrical generator	First fully operational device	Autonomous and operational WEC power plant
Waves	Representative power production and extreme sea states	Representative power production and extreme sea states	Pilot site waves	Operational and extreme sea states	Operational and extreme sea states
Experimental test objectives	Main: - Concept validation and optimisation - Power performance estimation - Assessing the impact of design variables and environmental parameters Possibly also: - PTO & mooring char. - Loads estimation - Movement estimation (RAO's)	Main: - Power performance estimation - Mooring and structural loads - Sea keeping - PTO conditions - Assessing the impact of design and environmental variables Possibly also: - Detailed numerical calc. - Feasibility study	Providing experimental data and experience on: - Power performance - Wave-to-wire model, including control strategy - Mooring and structural loads - Survival & sea keeping - Marine environment	Real cost and power production data for projection for device sales: - CAPEX - OPEX - Energy production And also - Wave-to-wire model - Structural and mooring forces - Lifecycle assessment	Real cost and power production data for projection for WEC array sales: - Array CAPEX - Array OPEX - Array Energy production And also for WEC array - Wave-to-wire model - Structural and mooring forces - Lifecycle assessment

The staged development process

- 1982 R. Palmer & Tritton: UK Wave Energy Program
- 1993 Commission of EC: Generic Technical Evaluation, Methodology for Reliability and Economic Assessment
- 2002 N.I. Meyer & K. Nielsen: Danish Wave Energy Program
- 2003 B. Holmes: Development & evaluation protocol - K. Nielsen (IEA OES): Practices for testing and evaluating of O.E.S. - G. Hagerman & R. Bedard: Guidelines for preliminary estimation of power production
- 2005 DNV: Guidelines on design and operation of WEC
- 2007 G. Smith & J. Taylor: Preliminary Wave Energy device performance protocol
- 2008 G. Payne: Guidance for experimental tank testing of WECs
- 2009 P. Frigaard & J.P Kofoed: Development of WECs - B.Holmes: Tank testing of WEC - E.Pitt: Assessment of performance of WEC
- 2010 B. Holmes & K. Nielsen: Development and testing guidelines & Extension testing and evaluating
- 2011 EquiMar: Protocols for equitable evaluation of marine energy converters
- 2012 J.P. Kofoed *et al.:* Methodology for performance assessment and presentation
- 2012 - ... IEC Technical Committee 114

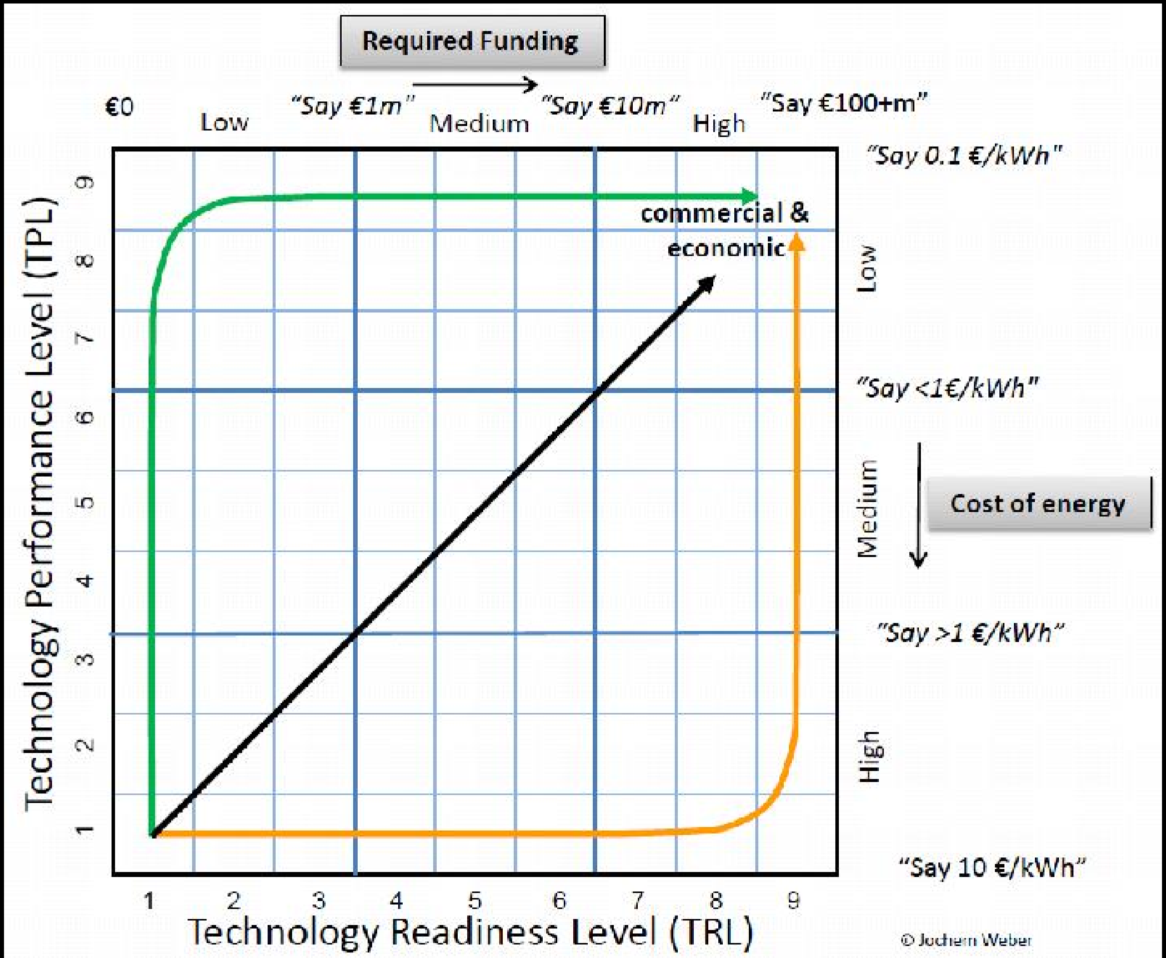
[Pecher, A 2012, Performance Evaluation of Wave Energy Converters. Ph.D. thesis, Department of Civil Engineering, Aalborg University, Aalborg. DCE Thesis, no. 38]
http://vbn.aau.dk/files/70080263/Performance_Evaluation_of_Wave_Energy_Converters.pdf

Funding the development



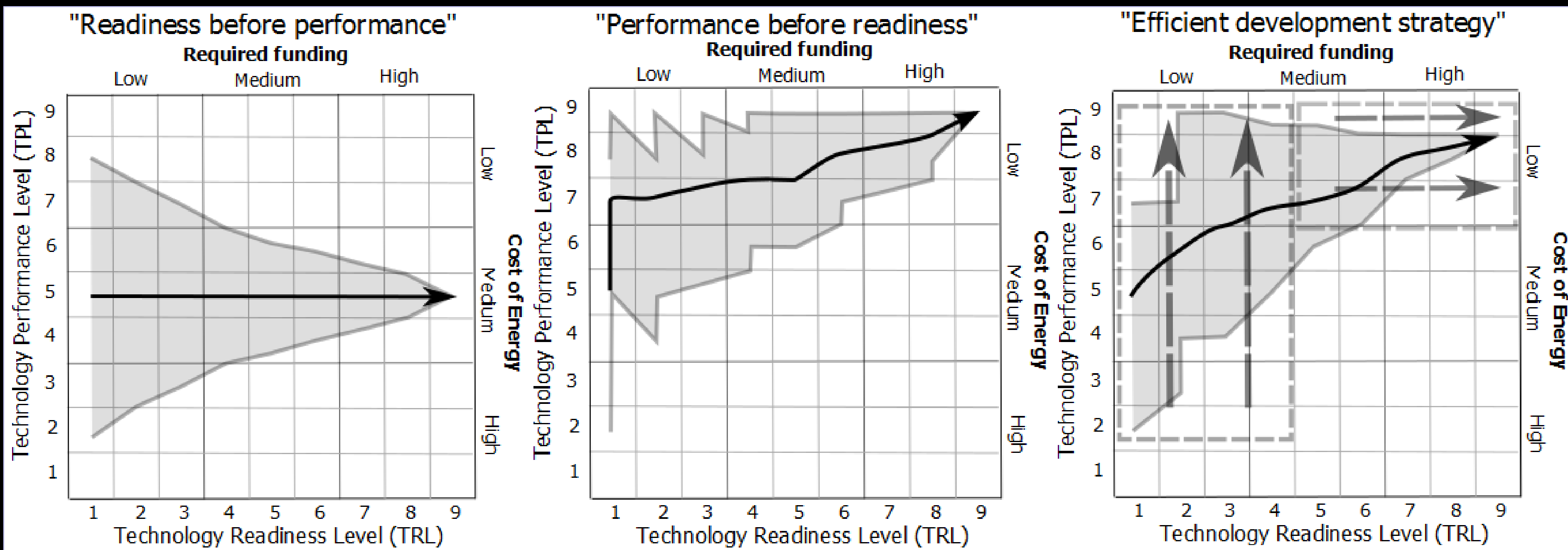
Technology Readiness and Performance Matrix

J. Weber



http://www.wavepowerconundrums.com/2013/02/nutshell-technology-readiness-performance-matrix.html

Techno-economic development strategies



Break?

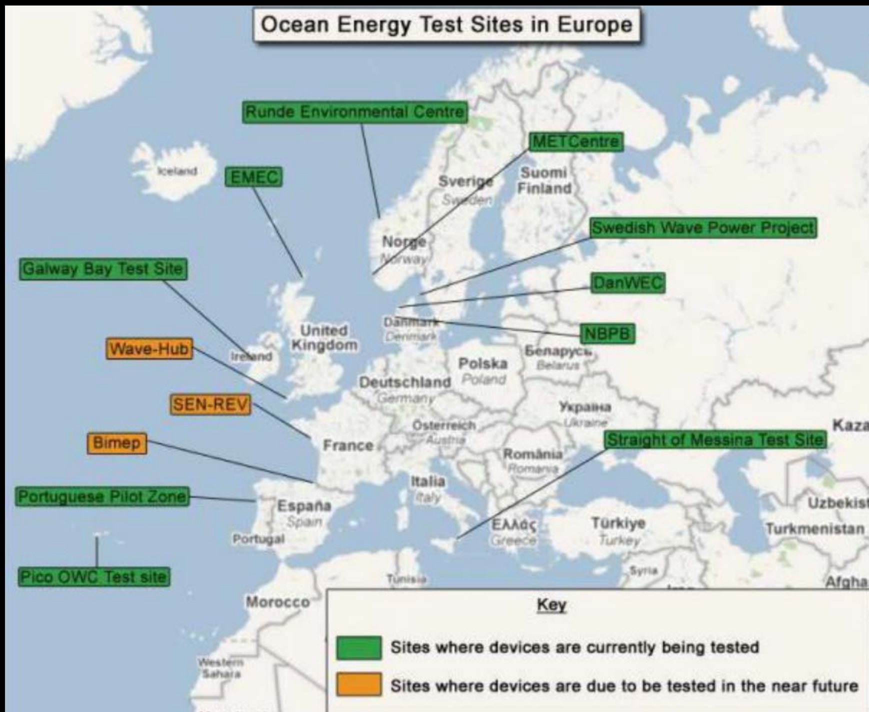
How did we get there in the wind sector ?

Early Flight

SILENT FOOTAGE

Learning is hard…

Test sites – DanWEC, an example



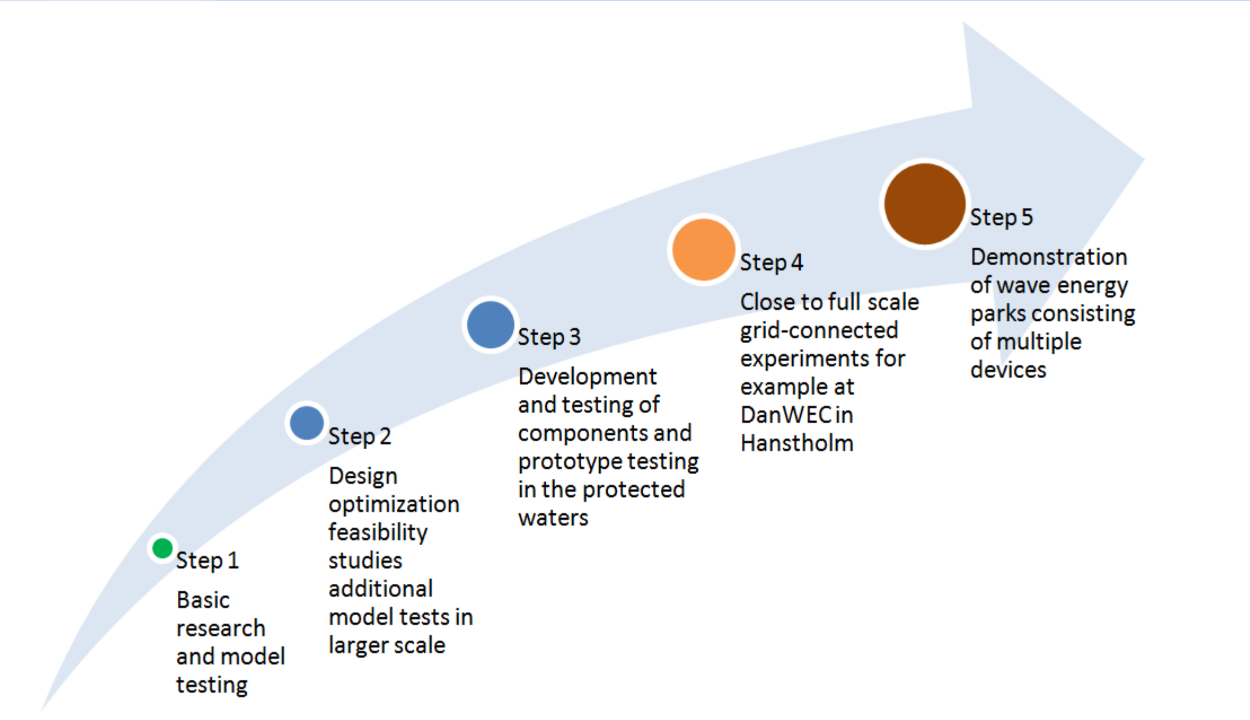
Hanstholm
DanWEC
Danish Wave Energy Center
NORTH DENMARK REGION
International port of Hanstholm Oceans of possibilities
THISTED KOMMUNE
Havneforum Hanstholm Oceans of possibilities
AALBORG UNIVERSITY

- Testing of pre-commercial WEDs
- Design basis
- Environmental monitoring
- Monitoring of devices
- Survailance, O&M assistance
- Link to research capacity
- Link to local services
- PR

National Green Labs funding secured

DanWEC

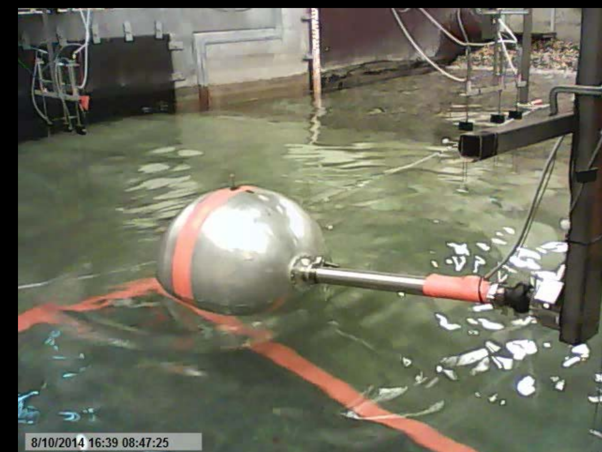
- **Aalborg (Laboratory)**
- **Nissum Bredning (Scale 1/10)**
- **Hanstholm (Scale 1/2)**



Site	Country	Power level [kW/m]	Water depth [meter]	Hs max (estimate) [meter]
EMEC	UK	21	50	15
Wave Hub	UK	17	50-65	14,4
Pilot Zone	PT	25	30-90	15,5 (d=30m)
bimep	Spain	21	50-90	11,4
Hanstholm	DK	6	20 - 30	6,5
Port Kembla	Australia	6,7	6	7
Galway Bay	Ireland	2,4	20-25	5
Nissum Bredning	DK	0,2	5-8	1,2

Wave basins and flumes

Aalborg university has the Hydraulics and Coastal Engineering Laboratories which are extensively used by the Wave Energy Research Group for experimental testing of WECs.



During the last ten years more than **30 wave energy projects** have been tested.

Two wave basins and three wave flumes are available

Test site in Nissum Bredning

Aalborg University has been involved in instrumentation, test and assessment of energy production from 6 different devices tested in Nissum Bredning (intermediate scale, real sea)

DanWEC in Hanstholm

For test, demonstration and assessment of energy production at large scale, real sea.

Partnership for wave power

A New Strategy for Development of wave energy, in June 2012

Key messages - To make the best use of available ressources for R&D:

- Cooperation (between both concept developers and specialists) around vital common components

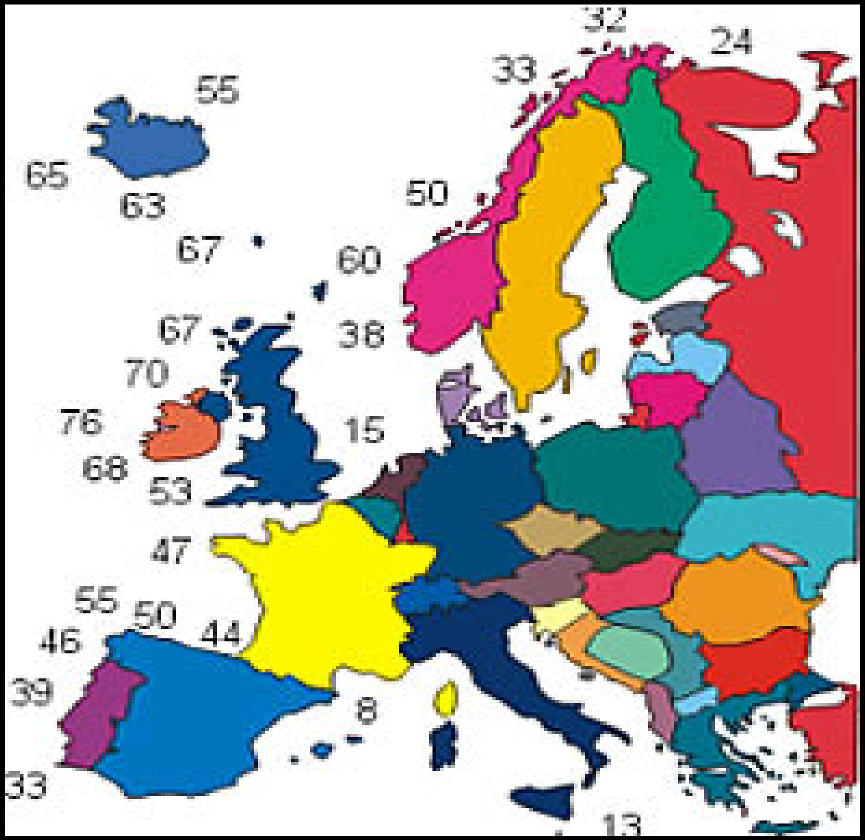
Prioritized focus areas:

- Mooring systems
- PTO systems
- Electrical transmission from floating device to seabed
- Materials and components
- Locations
- Facilities for demonstration of devices

Focus development through CoE calculations

Where is the interest?

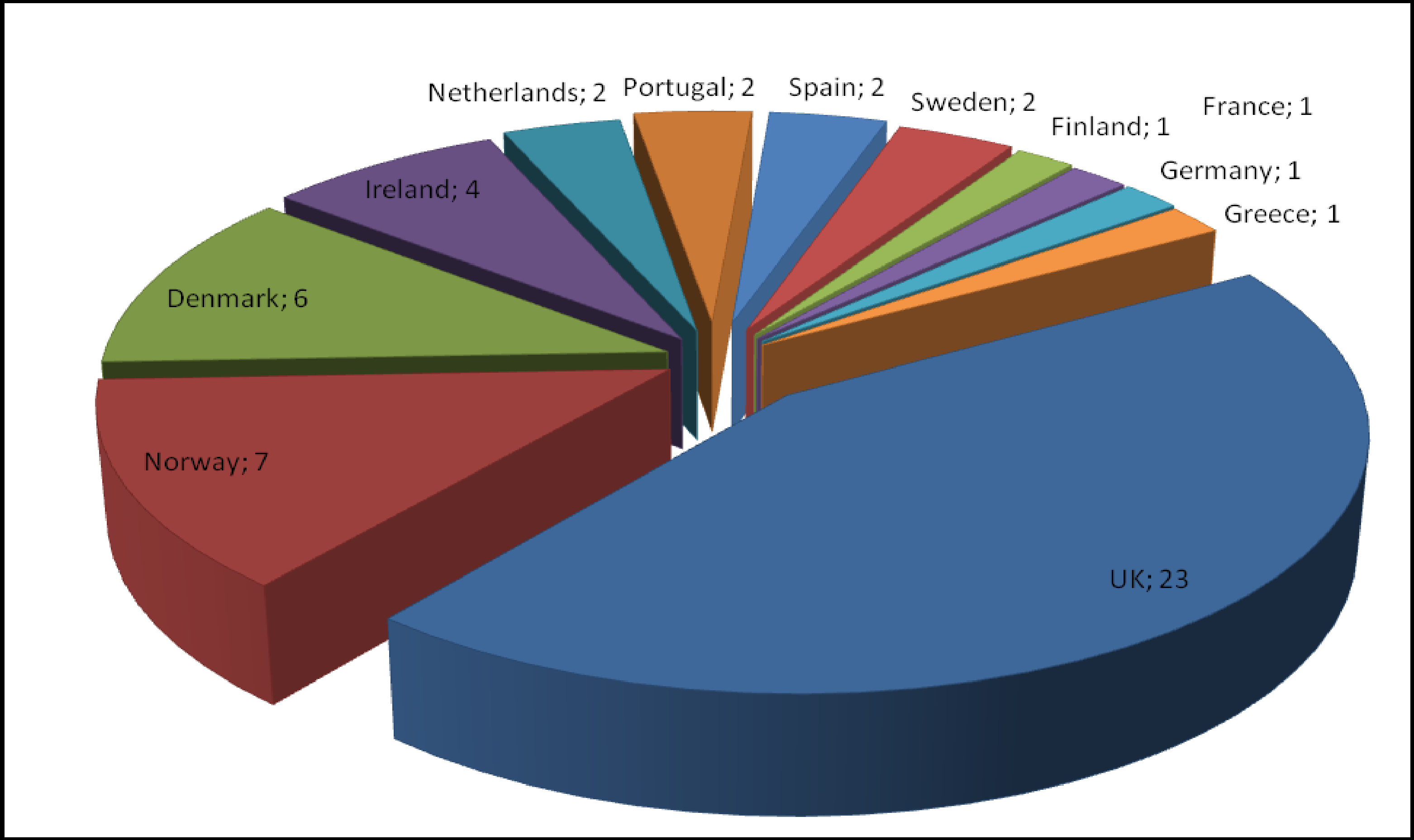
Ireland
Scotland
Wales
England
Portugal
Spain
Denmark
Norway
Sweden
Italy
Korea
New Zeeland
Australia
USA
Canada
…



Many companies world wide....

	COMPANY	TECHNOLOGY	COUNTRY BASE
1	Able Technologies L.L.C.	Electric Generating Wave Pipe	USA
2	Applied Technologies Company Ltd	Float Wave Electric Power Station	Russia
3	Aqua Energy / Finevara Renewables	Aqua Buoy	USA
4	Aquamarine Power	Oyster	UK
5	Atmocean	Atmocean	USA
6	AW Energy	Waveroller	Finland
7	AWS Ocean Energy	Archimedes Wave Swing	UK
8	Balkee Tide and Wave Electricity Generator	TWPEG	Mautitius
9	BioPower Systems Pty Ltd	bioWave	Australia
10	Bourne Energy	OceanStar ocean power system	USA
11	Brandl Motor	Brandl Generator	Germany
12	Caley Ocean Systems	Wave Plane	UK/Denmark
13	Checkmate Seaenergy UK Ltd.	Anaconda	UK
14	College of the North Atlantic	Wave Powered Pump	Canada
15	Columbia Power Technologies	Direct Drive Permanent Magnet Linear Generator Buoy / Permanent Magnet Rack and Pinion Generator Buoy / Contact-less Force Transmission Generator Buoy	USA
16	C-Wave	C-wave	UK
17	Daedalus Informatics Ltd	Wave Energy Conversion Activator	Greece
18	Delbuoy	Wave Powered Desalination	USA
19	DEXA Wave UK Ltd	DEXA Wave Energy Converter	USA
20	Ecofys	Wave Rotor	Netherlands
21	Ecole Centrale de Nantes	SEAREV	France
22	Edinburgh University	Sloped IBS Buoy	UK
23	ELGEN Wave	Horizon Platform	USA
24			
25	Embley Energy	Sperboy	UK
26	Energias de Portugal	Foz do Douro breakwater	Portugal
27	Float Inc.	Pneumatically Stabilized Platform	USA
28	Floating Power Plant ApS (F.P.P.)	Poseidon's Organ	Denmark
29	Fobox AS	FO3	Norway
30	Fred Olsen & Co./Ghent University	SEEWEC	Norway / EU
31	GEdwardCook	Syphon Wave Generator	USA
32	GEdwardCook	Floating Wave Generator	USA
33	Green Ocean Energy Ltd	Ocean Treader WEC	UK
34	Greencat Renewables	Wave Turbine	UK
35	GyroWaveGen	GyroWaveGen	USA
36	Hydam Technology	McCabe Wave Pump	Ireland
37	Independent Natural Resources	SEADOG	USA
38	Indian Wave Energy Device	IWAVE	India
39	Ing Arvid Nesheim	Oscillating Device	Norway
40	Instituto Superior Tecnico	Pico OWC	Portugal
41	Interproject Service (IPS) AB	IPS OWEC Buoy	Sweden
42	JAMSTEC	Mighty Whale	Japan
43	Joules Energy Efficiency Services Ltd	TETRON	Ireland
44	Lancaster University	PS Frog	England
45	Langlee Wave Power	Langlee System	Norway
	Leancon Wave Energy	Multi Absorbing Wave Energy Converter (MAWEC)	Denmark
46	Manchester Bobber	Manchester Bobber	UK
47	Martifer Energia	ONDA 1	Portugal
48	Motor Wave	Motor Wave	Hong Kong
49	Muroran Institute of Technology	Pendulor	Japan
50	Neptune Renewable Energy Ltd	Triton	UK
51	Neptune Systems	MHD Neptune	Netherlands
52	Norwegian University of Science and Technology	CONWEC	Norway
53	Ocean Energy Ltd	Ocean Energy Buoy	Ireland
54	Ocean Motion International	OMI Combined Energy System	USA
55	Ocean Navitas	Aegir Dynamo	UK
56	Ocean Power Technologies	Power Buoy	UK / USA
57	Ocean Wave Energy Company	OWEC	USA
58	Ocean Wavemaster Ltd	Wave Master	UK
59	Oceanic Power	Seaheart	Spain
60	Oceanlinx (formerly Energetech)	Denniss-Auld Turbine	Australia
61	Offshore Islands Limited	Wave Catcher	USA
62	Offshore Wave Energy Ltd	OWEL Energy Converter	UK
63	ORECon	MRC 1000	UK
64	OWWE (Ocean Wave and Wind Energy)	Wave Pump Rig	Norway
65	Pelagic Power AS	PelagicPower	Norway
66	Pelamis Wave Power	Pelamis	UK
67	Renewable Energy Holdings	CETO	AUS / UK
68	Renewable Energy Pumps	Wave Water Pump (WWP)	USA
69	Sara Ltd	MHD Wave Energy Conversion (MWEC)	USA
70	SDE	S.D.E	Israel
71	Sea Power International AB	Streamturbine	Sweden
72	Seabased AB	Linear generator (Islandsberg project)	Sweden
73	Seawood Designs Inc	SurfPower	Canada
74	SEEWEC Consortium	FO3 device, previously as Buldra	UK
75	SeWave Ltd	OWC	Faroe Islands
76	Sieber Energy Inc	SieWave	Canada
77	SRI International	Generator utilizing patented electroactive polymer artificial muscle (EPAMT) technology	USA
78	Swell Fuel	Lever Operated Pivoting Float	USA
79	SyncWave	SyncWave	Canada
80	Trident Energy Ltd, Direct Thrust Designs Ltd	The Linear Generator	UK
81	Union Electrica Fenosa of Spain	OWC	Spain
82	University of Edinburgh	Salter's Duck	N.A.
83	Vortex Oscillation Technology ltd	Vortex oscillation	Russia
84	Wave Dragon	Wave Dragon	Wales / Denmark
85	Wave Energy	Seawave Slot-Cone Generator	Norway
86	Wave Energy Centre (WaVEC)	Pico plant	Portugal
87	Wave Energy Technologies Inc.	WET EnGen™	Canada
88	Wave Energy Technology	(WET-NZ)	New Zealand
89	Wave Power Group	Salter Duck, Sloped IPS	UK
90	Wave Star Energy ApS	Wave Star	Denmark
91	Waveberg Development	Waveberg	Canada
92	WaveBob Limited	Wave Bob	Ireland
93	Wavegen (Siemens)	Limpet	UK
94	Wavemill Energy	Wavemill	Canada
95	WavePlane Production	Wave Plane	Denmark
96	WindWavesAndSun	WaveBlanket	USA

Half of them in Europe…



What has been installed?

5-10 MW pilot plants – list by no means complete!

- Pelamis, Portugal – 3x 0.75 MW, 2x 0.75 MW at EMEC
- Oyster, AquaMarine, EMEC, 2x 0.8 MW
- Wavestar, Hanstholm, 0.1 MW
- Limpet, Islay – 0.5 MW
- Indian OWC
- Pico Azores
- Mutriko OWC
- Seabased Lysekil
- CETO Carnegie
- The Eagle, China
- Fred Olsen Lifesaver, Falmouth and Hawaii

More installations showing up all the time!

How many are working with wave energy?

Full-time jobs in the sector (Denmark):

Concept developers: Wave Star 5, Wavepiston 4, Wave Dragon 2, Weptos 2, Crestwing 2, LeanCon 1 …

Universities: AAU 15-20, DTU 5

Consultancies etc.: ~10. DHI, Balslev, Niras, KK, …….

The sector is small but still something like 100 full time jobs in Denmark.

A guess on the global number of people working within the sector could be 2-5000.

Socio economic & environmental impacts

10-20 jobs per MW installed
Mainly in Remote Areas

Requirement for more Energy Storage

Environmental Impact on the Ocean
Totally New way of using the Ocean

Who are interested in wave energy?

- Oil Companies become Energy Companies.
- Growing interest from media and public. WERG has often journalists/television visitors.
- Still new inventions coming out every year.
- Increased demand for courses on the subject.
- Ministers.
- Regions.
- Companies calling asking for good projects to invest in.
- IEC Standardisation – national mirror committees.
- Network of Ocean Energy Professionals www.oceanenergy-europe.eu
- INORE www.inore.org
- …

Who are investing ?

- National Governments
- EU
- Private Companies – industrial investors
- Private Companies – financial investors
- Utillities
- Universities

- 40-60% public money.

Barriers to overcome

- Legal Framework
- Long term politics
- Feed-in tarifs to create incentives for investments that can bring costs down
- Re-organisation of the Energy Sector

Change of focus

Political wish for securing supply

$\Downarrow$

Creation of jobs (financial crisis)

Focus on technology (especially hydraulic performance)

$\Downarrow$

Focus on a of technology, organisation and financing

Seen from outside the lack of organization
is a significant barrier for many developers

Summary

Wave Energy is today a possibility

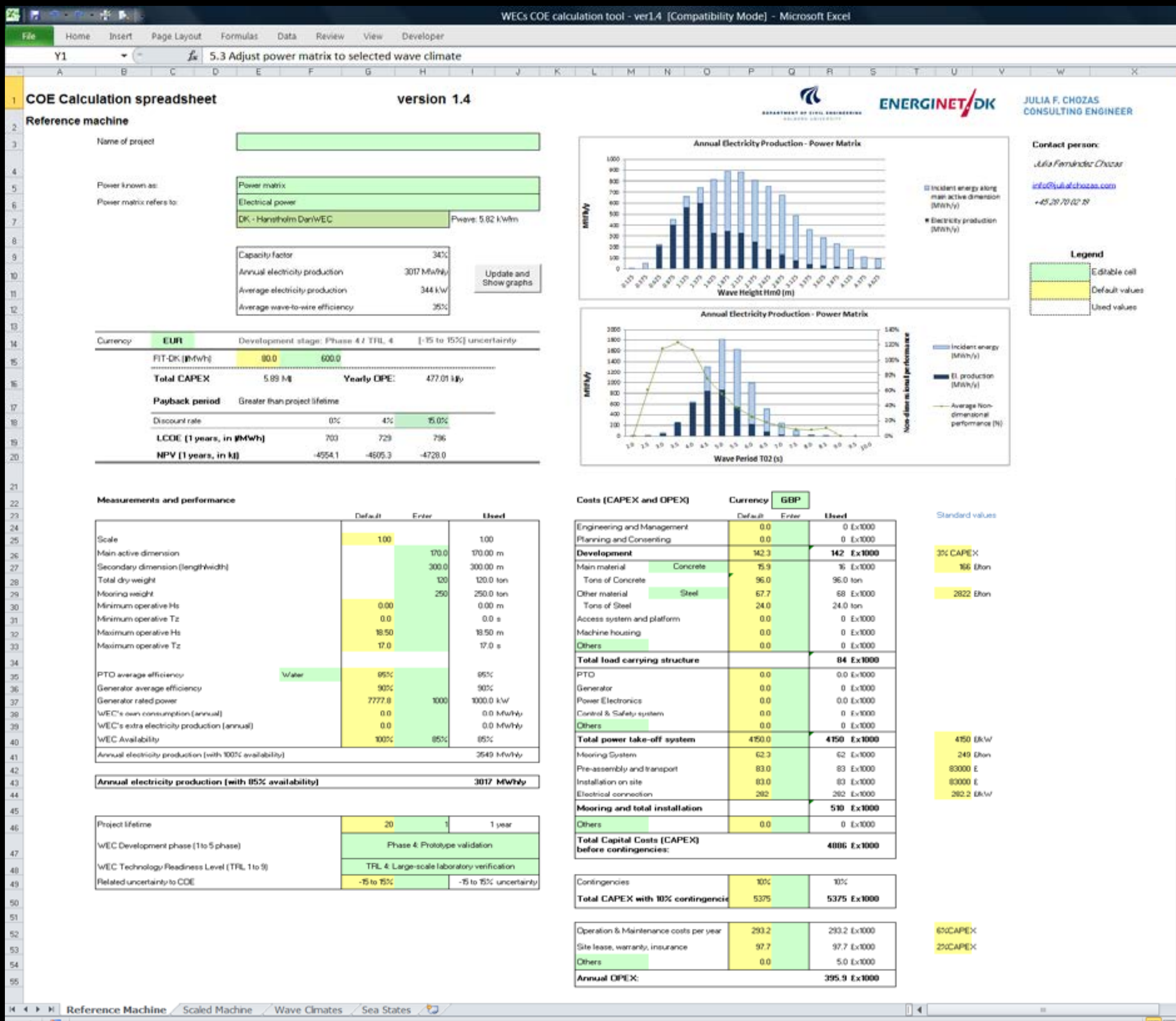
Wave Energy has the potential to contribute significantly to the worlds energy production

To make sense WEC must be build in large scale and deployed at deep water, which again means large investments

Today there is a growing demand for clean energy, which means that we never know

There are so many nice engineering challanges related to Wave Energy

COE Calculation Tool



energinet.dk

http://energinet.dk/DA/KLIMA-OG-MILJOE/Energi-og-klima/Forskning-i-vedvarende-energi/Sider/Boelgekraft.aspx

http://vbn.aau.dk/en/publications/user-guide--coe-calculation-tool-for-wave-energy-converters%2878b135d9-ea66-43f8-959f-c799dc4df1a9%29.html

http://www.juliafchozas.com/projects/coe-calculation-tool/

IEA-OES

http://www.ocean-energy-systems.org/news/international-lcoe-for-ocean-energy-technology/

Locations on the COE Tool

Some major collaborative projects

MaRINET

Structural Design of Wave Energy Devices (SDWED) – DK (DSF)

Optimal Design Tools for Ocean Energy Arrays (DTOcean) – EU (FP7)

Standardization related to wave energy IEC TC 114

Digital Hydraulic Power Take Off for Wave Energy – DK (ForskEL)

FLOAT2 – New Flexural UHPC Application for Wave Converters 2 - DK (ForskEL)

Mooring solutions for large wave energy converters – DK (EUDP)

…

SDWED

The Alliance – The Project: Structural Design of Wave Energy Devices

Objective of the project

Strengthen and consolidate Denmark's position as one of the leaders in wave energy research, through the formation of a **strategic international research alliance** focusing on the structural design of Wave Energy Devices

Project granted by the **Danish Council for Strategic Research**
Call: **Strategic Research in Sustainable Energy and Environment**
Theme: **Energy Systems of the Future**

5 years (2010-2014)

12 Partner organizations - 6 Danish (73 %), 6 International (27 %)

Budget: 25 mil. dkr. (19.6 DSF, 5.4 Co-fin.)

Funded by
Det Strategiske Forskningsråd

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Objectives

- Increase knowledge on loads on Wave Energy Devices, primarily through the **development of models** for floating structures taking into account hydrodynamics, moorings and power take-off; and the establishment of **protocols for design** of Wave Energy Devices.
- Create **lasting relations** between Danish and international top institutions working in the field to achieve greater research capability.
- **Increase the reliability** and **decrease the cost** of Wave Energy Devices in such a way that they can feasibly contribute to energy supply.
- Finally, the main societal objective is to **improve and consolidate the competitiveness** of Danish wave energy, repeat the 'Danish Wind Adventure' in a new sector and thus create both **growth and knowledge-intensive jobs** for Danish society.

What did we want to achieve?

Overall: Reduce cost of energy….

Need tools for WED design and optimization

Different needs in

- Operating conditions
- Extreme conditions

Focus on

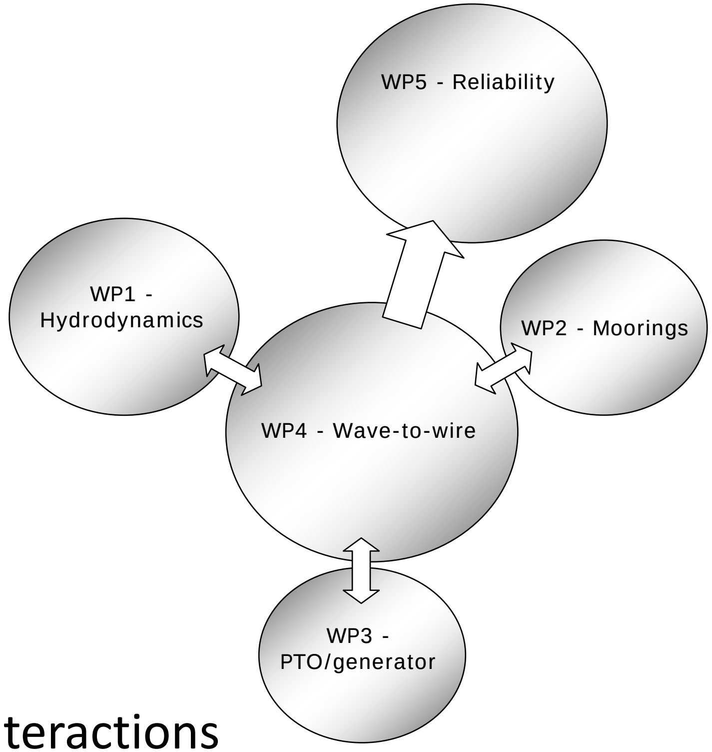
- Power production optimization
- Structural design

Many different WED types

- Provide ’building blocks’

Complex systems, non-linear behavior and interactions

- Need to balance computational speed and accuracy



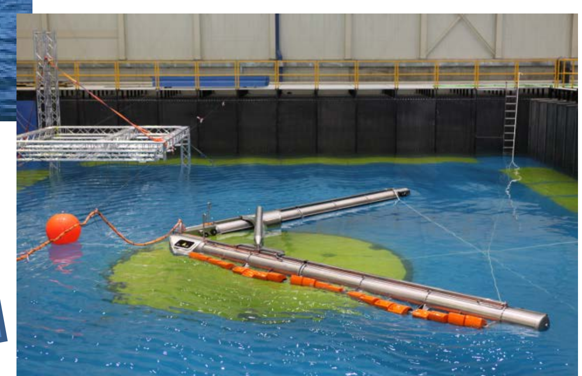
SDWED

Project test cases

Wavestar:
Operating cond.:
HD – lin./non-lin.
Moorings – N.A.
PTO – time dom. adv. control
Extreme cond.:
Simple – floaters out of water

Dexawave:
Operating cond.:
HD – lin.
Moorings – important, interaction
PTO – simple, passive damping
Extreme cond.:
CFD for structural loading
Moorings – dyn. analysis

Weptos:
Operating cond.:
HD – multibody, highly non-linear, hydrostatics, variation of geometry
Moorings – important, weak interaction
PTO – highly non-lin.
Extreme cond.:
CFD for structural loading
Moorings – dyn. analysis



Increasing complexity

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Researcher training

Ph.D.'s	Post Doc.'s
Andrew Zurkinden, AAU-C	Morten Kramer, AAU-C
Simon Ambühl, AAU-C	Robert Read, DTU
Torben Christensen, DTU	
Francesco Ferri, AAU-C	

Autumn 2010	**Ocean Energy Structures, 1 ECTS**	AAU: JPK
28-10-2010	Lecture 1: Overview of the wave energy sector / The Wave Dragon Case	JPK
12-10-2010	Lecture 2: Overview of existing wave energy converter technologies	JPK
26-10-2010	Lecture 3: Hydraulic and structural evaluation and development of wave energy	JPK
02-11-2010	Lecture 4: Performance evaluation of wave energy concept prototypes	JFC
09-11-2010	Lecture 5: Integration of wave energy into the grid	JFC
Nov. 2010	**Master lecture at Helsinki University: Wave Energy Challenges - How to harness the ressource**	WAVEC,
22-25.03.2011	**Lectures at Padova and Bologna University, Italy (8 hours in total) on Maritime Energy**	AAU: PF
	Lecture [illegible]: Risks related to the development of Maritime Energy (4 hours)	
	Lecture 5: EIA of Maritime Energy (1 hour)	
	Lecture 6-7: Wave Forces on Structural Elements on Maritime Energy Devices (2 hours)	
	Lecture 8: Protocol for Development of Maritime Energy (1 hours)	
Spring 2011	**Ph.D. courses on Wave Energy Utilization, 3 weeks at AAU**	AAU: JPK
03-06.05.2011	Introduction to Wave Energy Utilization, 2 ECTS - 7 Lectures	AAU: LM,
09-13.05.2011	Experimental Testing for Wave Energy Utilization, 3 ECTS - 13 Lectures	AAU: JPK
16-20.05.2011	Advanced Control Theory for Wave Energy Utilization, 3 ECTS - 17 Lectures	AAU: MK,
Jan. 2012	**Lectures on Exp. Testing for Wave energy Utilization, Arr. by Israel Martinez Barrios, Acciona Energía, Spain ?**	AAU: JPK

To date 45 ECTS (~182 lectures) given

e.g. PhD courses in 2011, 2012, 2013

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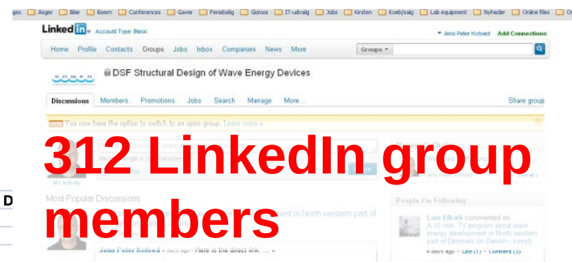
Publication and dissemination

Journal / Publication name	Issue	Volume	Year	Publication Title	Lead Author	Affiliation	Co-Athours	Affiliation
ICASP 2011, Zurich, Switzerland				Probabilistic Design of Wave Energy Devices	[illegible] Sørensen	[illegible]	Jens Peter Kofoed	AAU
ICOE 2010, Bilbao, Spain				Modelling of the Overtopping Flow on the Wave Dragon Wave Energy	Parmeggiani, S.	AAU	Pecher, A., Kofoed	AAU
10th Symposium on Overset Composite Grids and Solution Technology.				Multiple-domain finite difference solutions for oceanwave-structure int	Robert Read	DTU	Harry Bingham	DTU
National Conference: Convegno Nazionale di Idraulica e Costruzioni Idr				Wave structure interaction in an overtopping based wave energy co	[illegible]	[illegible]	[illegible]itini, L. &	UniBo
ICS2011, Szczecin, Poland				Wave loadings acting on an innovative breakwaters for energy production	Vicinanza, D.	[illegible]	[illegible], F., Buccin	.../AAU
ICOE 2010, Bilbao, Spain				Integration of Wave Energy Converters into Coastal Protection Schem	Zanuttigh, B.	UniBo	Martinelli, L., Ruol,	UniBo/AAU
ICREPQ 2011, Las Palmas, Spain				Wave Energy Power Output Variability of Different Wave Energy	[illegible]Chozas, J.	[illegible]	[illegible] H.C., He	.../AAU
Risø Energy Report 9 - Non-fossil energy technolo	9		2010	Hydropower, Chap. 7	[illegible]	[illegible]	[illegible] P.	AAU
ISOPE 2011, Hawaii, US				Performance assessment of the Pico OWC power plant following the E	Pecher, A.	AAU	Le Crom, I, Neuma	WAVEC/AAU
EWTEC 2011, Southhampton 2011				Wave Pressures and Loads on a Small Scale Model of the Svaheia SSG	M. Buccino	Uni. Naples	D. Vicinanza, F. Cia	Uni. Naples
EWTEC 2011, Southhampton 2011				Experiments on the WavePiston, Wave Energy Converter	[illegible] Ange[illegible]	UniBo	[illegible]igh, J. P.	UniBo, AAU,
EWTEC 2011, Southhampton 2011				Equimar: Development of Best Practices for the Engineering Performa	C. M. Johnstone	Uni. Strathclyde	.. many .. J. P. Kofo	a. o. AAU
EWTEC 2011, Southhampton 2011				Experimental Testing of the Langlee Wave Energy Converter focusing	J. Lavelle	AAU	J. P. Kofoed	AAU
EWTEC 2011, Sou[illegible]				[illegible]ability of the Power Output of Three Wave Energy Technologies	J. F. Chozas	AAU	a. o. J. P. Kofoed	AAU
EWTEC 2011, Sou[illegible] 2011				Hydrodynamics around DEXA devices and implications for coastal prot	M. Castagnetti	UniBo	B. Zanuttigh, E. An	UniBo, AAU,
EWTEC 2011, Southhampton 2011				Performance Assessment of the Wave Dragon Wave Energy Converte	S. Parmeggiani	AAU	J. F. Chozas, A. Pe	AAU, WD

SDWED Symposia
1st: 46 participants
2nd: 70 participants
3rd: 49 participants

84 papers published

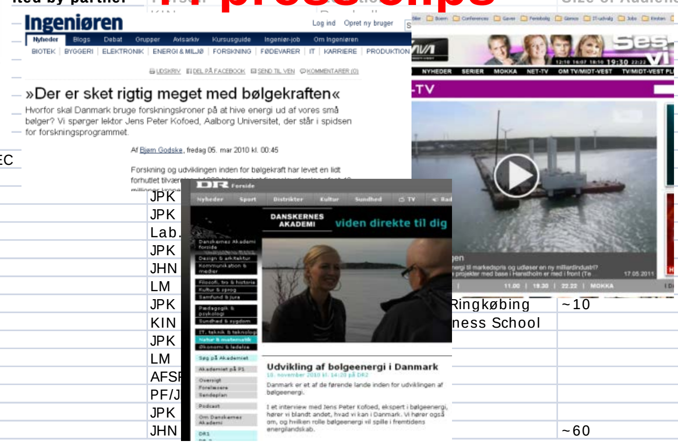


312 LinkedIn group members

Project website

Date	Event	Presentation title	Presented by partner			Size of Audience
						15
						100
						100
06-05-2010	ICTNORCOM arr. i Hanstholm	BrainsB[illegible]				
19-05-2010	Viborg Technical High School	General[illegible]				
20-05-2010	Bølgekrafttræf / Ocean Energy Open Days	Wave E[illegible]				25
18-06-2010	Visit by Danish and Norwegian Utility Leaders	Status [illegible]				16
11-09-2010	Siemens Wind Power Family Day	Exhibition of small wave flume with overtopping device	AAU			
26-09-2010	Seminar 'Who is who' in Offshore Renewable Energy	Public entities training on wave energy	WavEC			
29-09-2010	DNF Naturvidenskabsfestivalugen 2010	Når bølgerne går højt	AAU			
30-09-2010	DNF Naturvidenskabsfestivalugen 2010	Når bølgerne går højt	AAU	JPK		
01-10-2010	DNF Naturvidenskabsfestivalugen 2010	Når bølgerne går højt	AAU	JPK		
27-0[illegible]	[illegible]	[illegible]	AAU	Lab.		
[illegible]10-2010	[illegible]	[illegible]	AAU	JPK		
09-11-2010	HTX Sønderjylland	Når bølgerne går højt	AAU	JHN		34
10-11-2010	Nørresundby Gymnasium	Når bølgerne går højt	AAU	LM		120
[illegible]	[illegible]geenergi	Utilization of Wave Energy – potentials, challenges and	AAU	JPK	Ringkøbing	~10
29-10-2010	Fra Samling til Handling, Grøn offshore alliance	Danish Wave Energy Activities international perspective	RAM	KIN	[illegible]ness School	40
18-01-2011	IDA arr. on Wave Energy	Hvad er bølgeenergi?	AAU	JPK		38
18-03-2011	YOUNG ENERGY konference		AAU	LM		
06-04-2011	Forskningensdag, Inst. For Byggeri og Anlæg	Performance assessment of Wave Energy Converter	AAU	AFS[illegible]		70
11-04-2011	Visit by Connie Hedegaard to DanWEC, Hanstholm	Aalborg Universitets aktiviteter indenfor vedvarende en	AAU	PF/J[illegible]		15
23-05-2011	Visit by Reza UHM	RE projects at UHM	AAU	JPK		12
27-05-2011	SKUB Elevuniversitet	Bølgeenergi	AAU	JHN		~60

59 invited lectures and public presentations



44 press clips

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SDWED

Resources at project website

http://www.sdwed.civil.aau.dk/

What can you find there?

- Publications
- Theses
- Software
- Deliverables

Will be updated over the remaining part of the project – keep an eye on it!

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S D W E D

Associated activities

Danish Partnership for Wave Power

- Strategi, Roadmap projekt

DanWEC (Green Lab)

Allocation of 25 mill. dkr. for wave power 2014-15

EWTEC 2013

Marinet

FLOAT2

Digital Hydraulic Power Take Off for Wave Energy

DTOcean

DS S-614 (IEC TC-114)

Mooring Solutions for Large Floating WECS (pending)

WaveSpring (pending)

- and many more....

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SDWED

Check-up on goals and objectives…

- **Strategic international research alliance - Lasting relations** ✓

  Corporative network established, continued collaboration on future projects

- **Development of models** and **protocols for design** ✓

  Models developed and made available, participation in standardization efforts

- **Increase the reliability** and **decrease the cost** (✓) Still some way to go…

  Methodologies established and demonstrated

- **Improve and consolidate the competitiveness** ✓

  Danish wave energy sector more coherent

- **Creation of growth and knowledge-intensive jobs** Still some way to go…

  Sector still far from industrial scale

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The International Research Alliance

Funded by

Danish Agency for Science Technology and Innovation
Ministry of Science Technology and Innovation

Thank you for your attention!

S D W E D

STRUCTURAL DESIGN OF WAVE ENERGY DEVICES

AALBORG UNIVERSITY
Department of Civil Engineering

DTU Technical University of Denmark

RAMBØLL

DHI

AALBORG UNIVERSITY
Department of Energy Technology

WaveEnergy Centre
Centro de Energia das Ondas

COPPE UFRJ

Fraunhofer

THE UNIVERSITY OF EDINBURGH

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

DNV

Break?

Overview of Wave Energy Converters

- Oscillating Water Columns



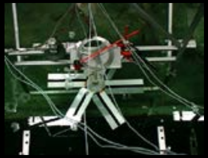
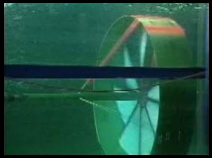
- Overtopping devices




- Point absorbers



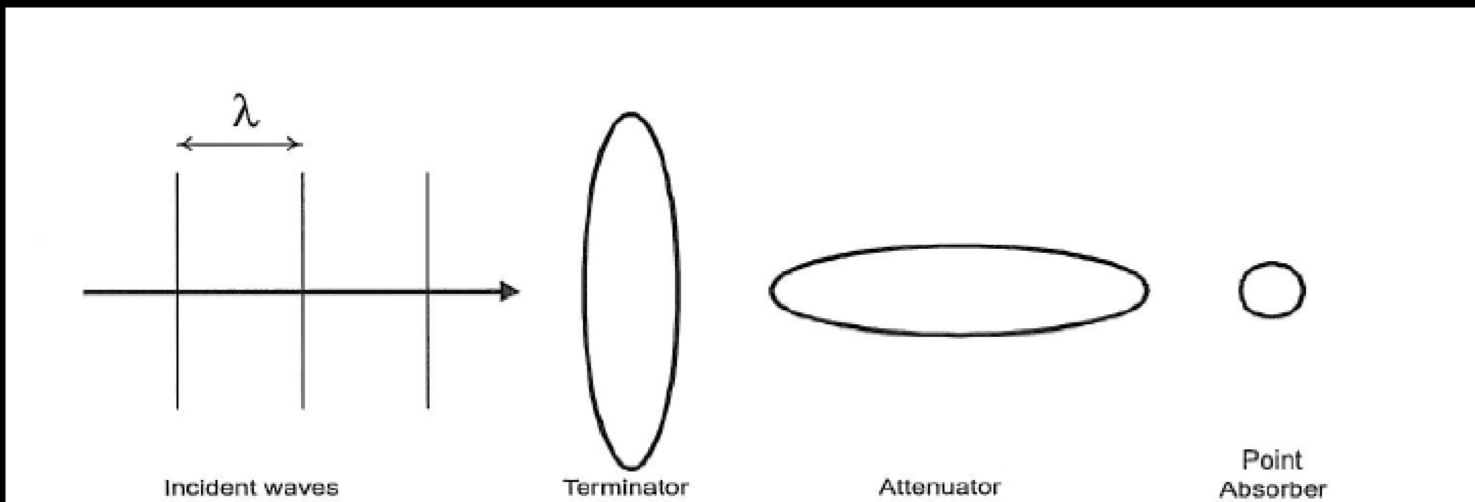

- Wave Mills

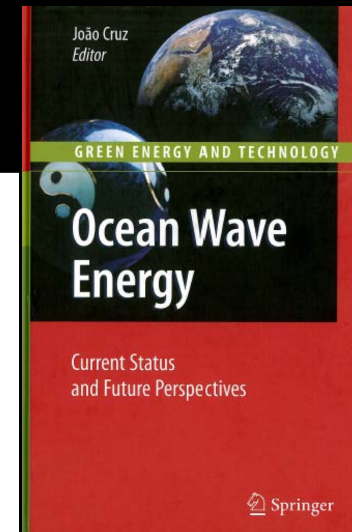




- And many others



Categorization of WECs





Often used:

- Terminators
- Point absorbers
- Attenuators

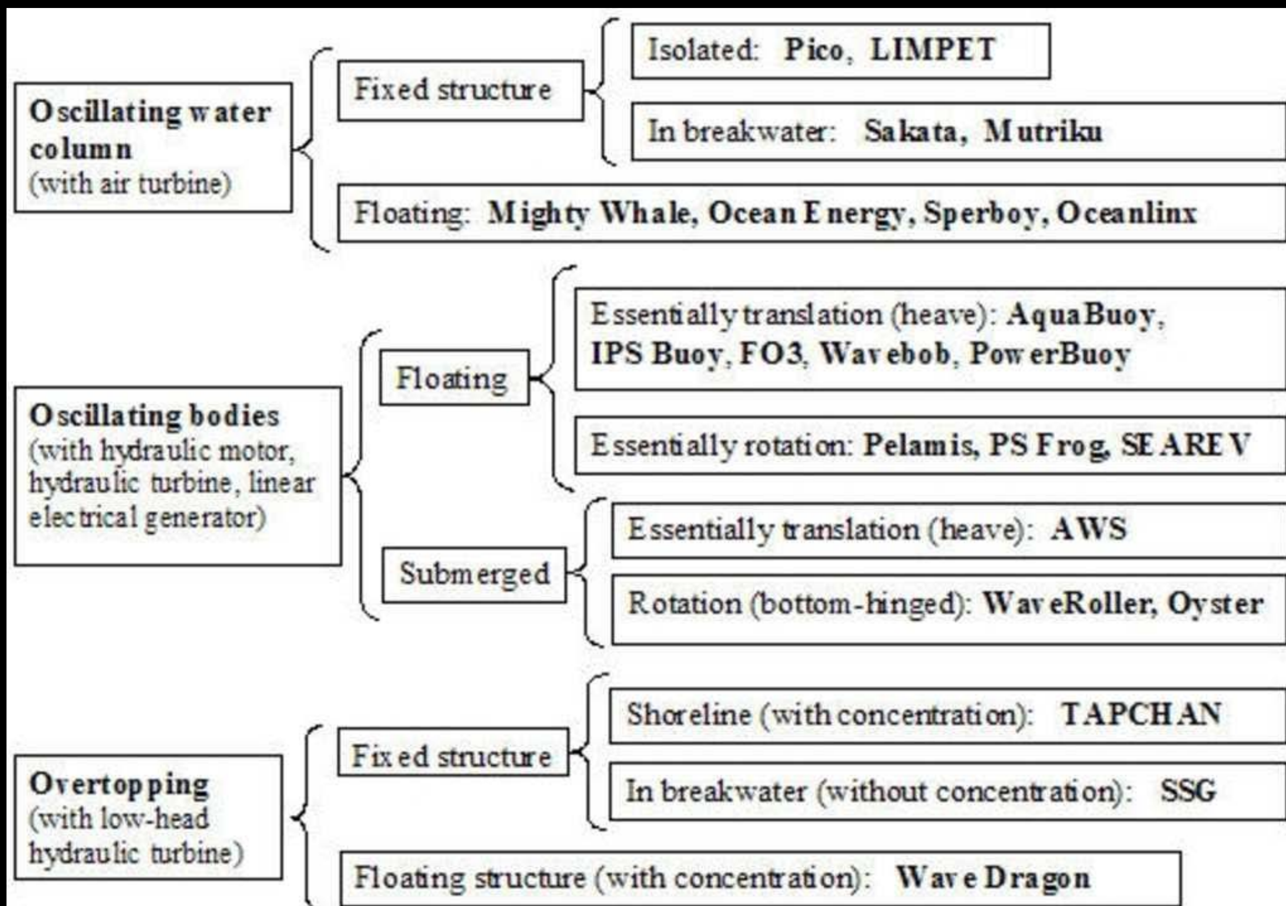
By location:

- Onshore
- Nearshore
- Offshore

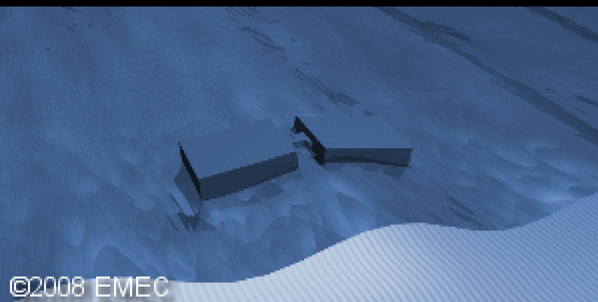
By level of development:

- First generations
- Second generations
- Third generations

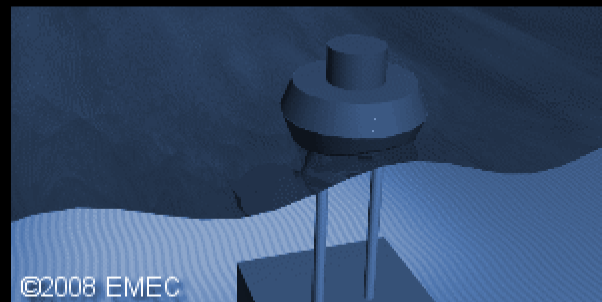
Categorization of WECs (IEA-OES)



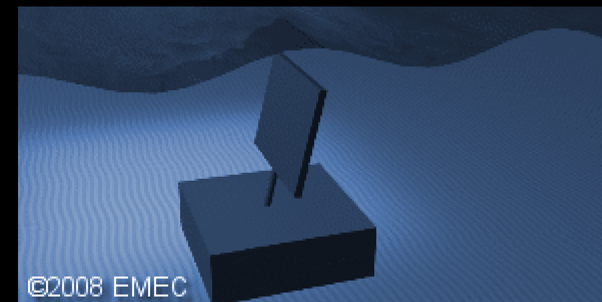
Classification by tecnologies (EMEC)



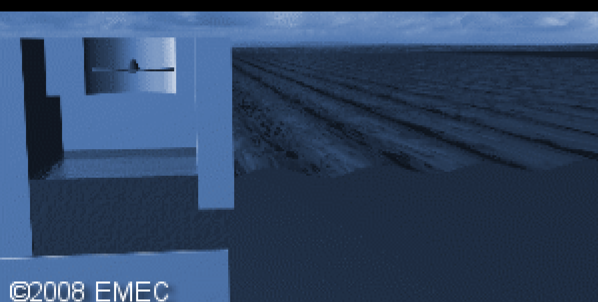
Attenuator



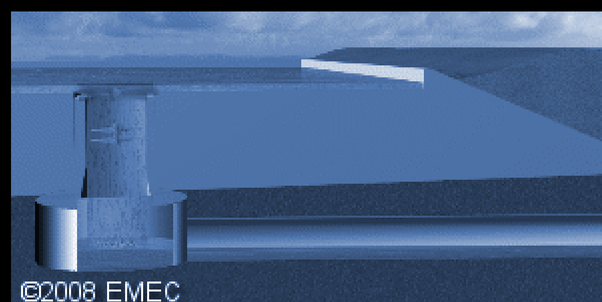
Point Absorber



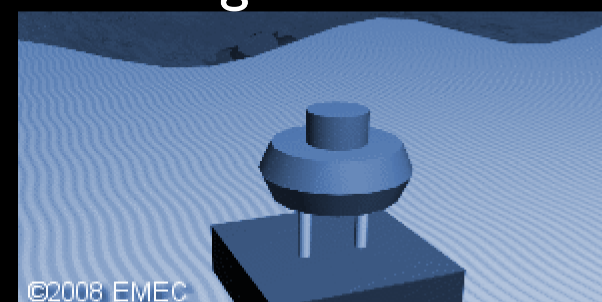
Oscillating Wave Surge Converter



Oscillating Water Column



Overtopping Device

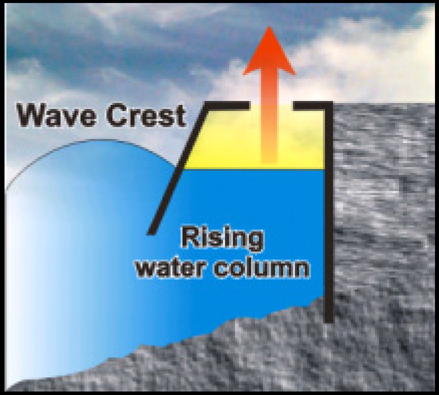


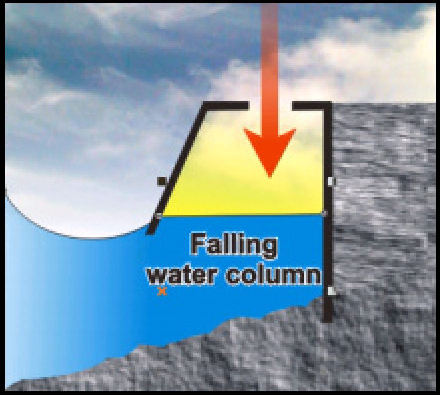
Submerged Pressure Differential

Others…

Oscillating Water Columns (OWC)

- Principle



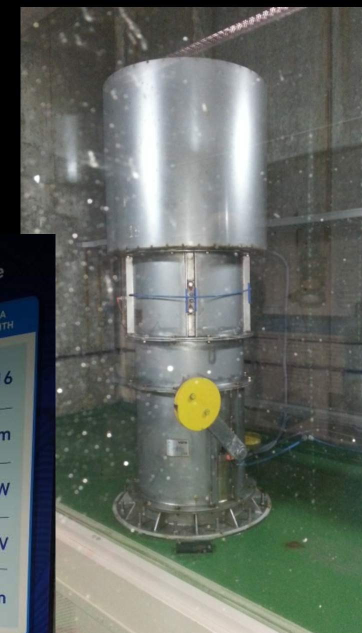


- Wells turbine

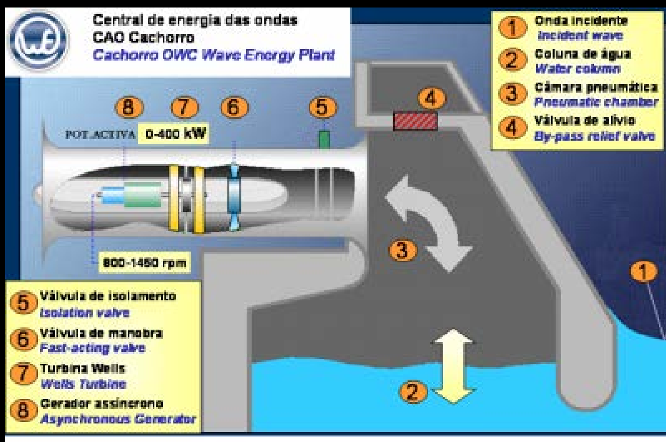
OWCs

Wavegen, LIMPET, Islay

Wavegen, Mutriku, Spain



Pico OWC

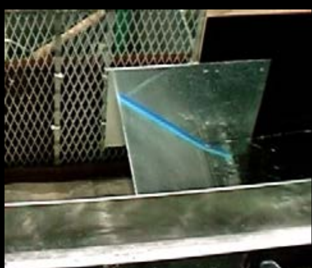


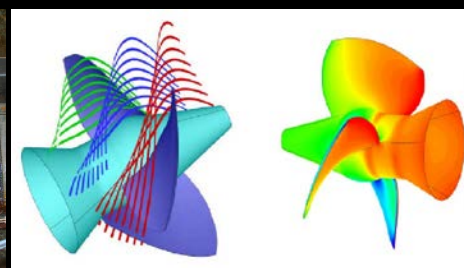
Up to 10 OWC prototypes world wide…

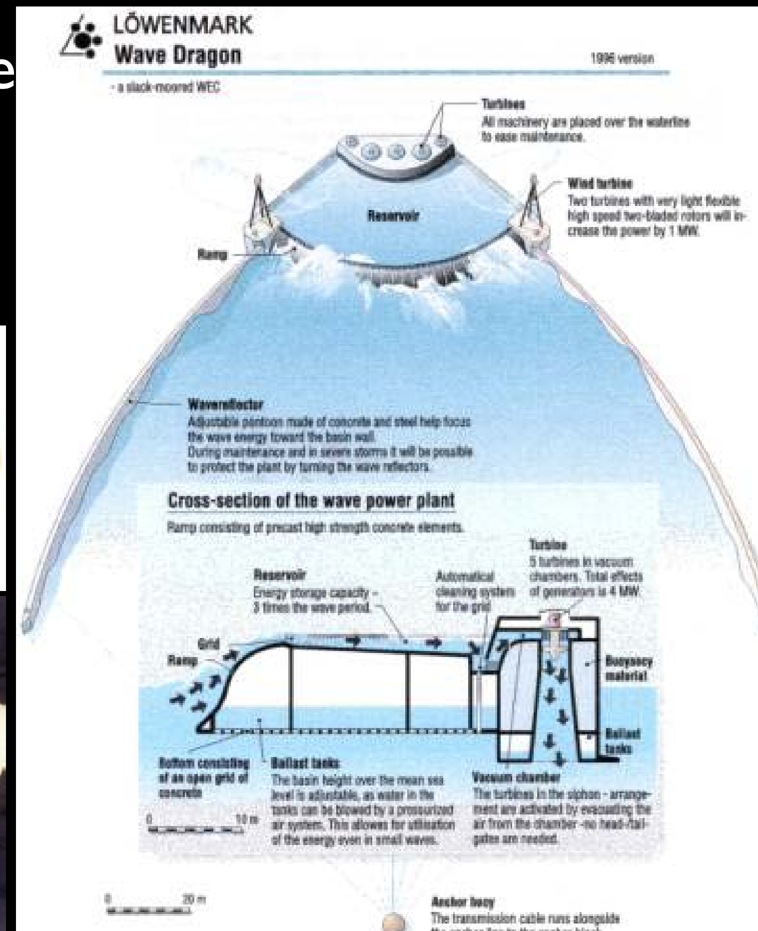
LeanCon OWC

Overtopping devices

Principle



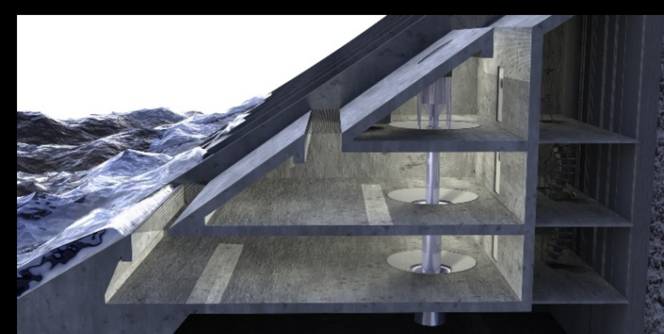




Overtopping devices

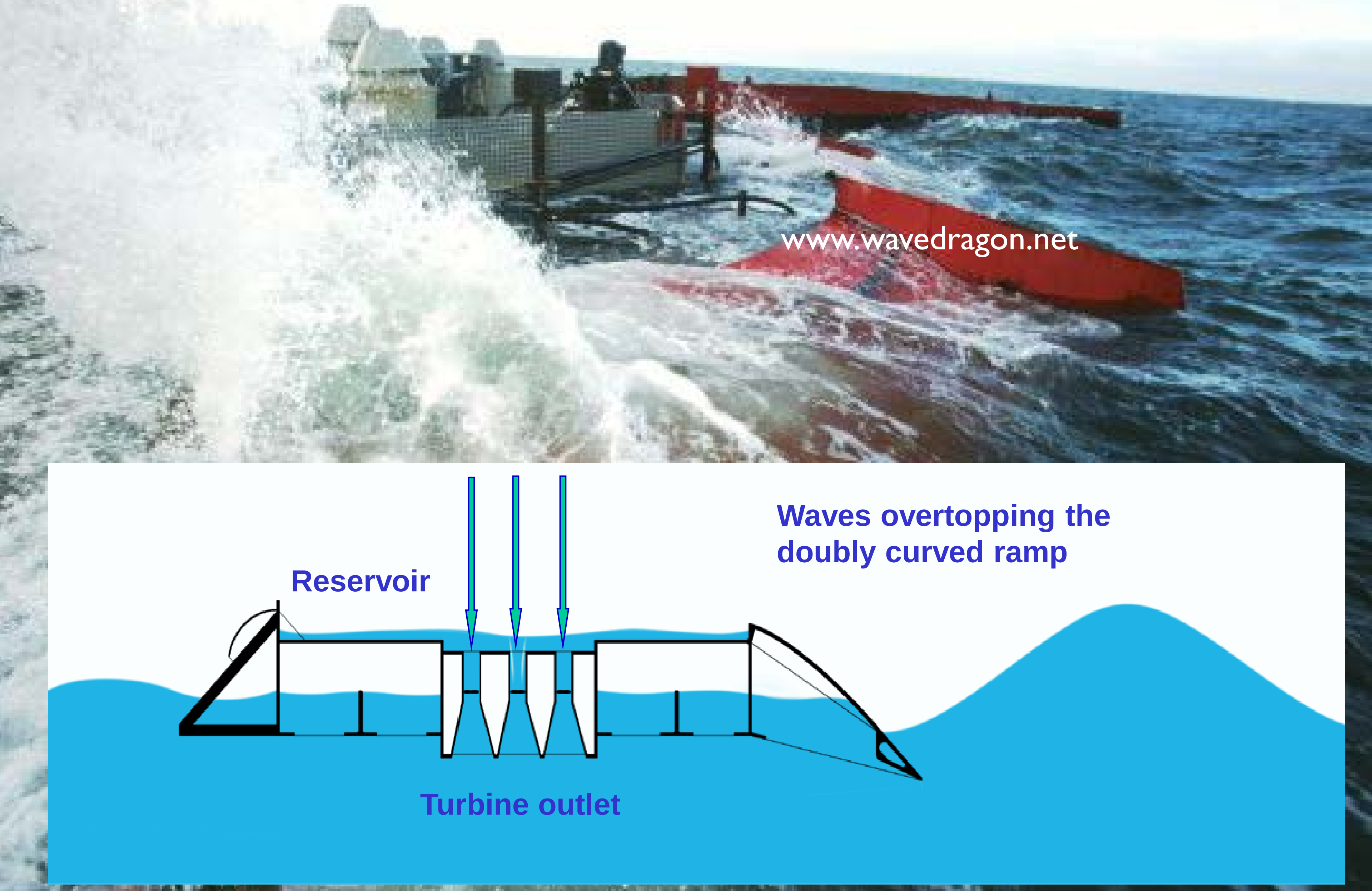
Wave Dragon.net

SSG WAVEenergy



Wave Dragon

- a slack moored wave energy device of the overtopping type



Wave Dragon

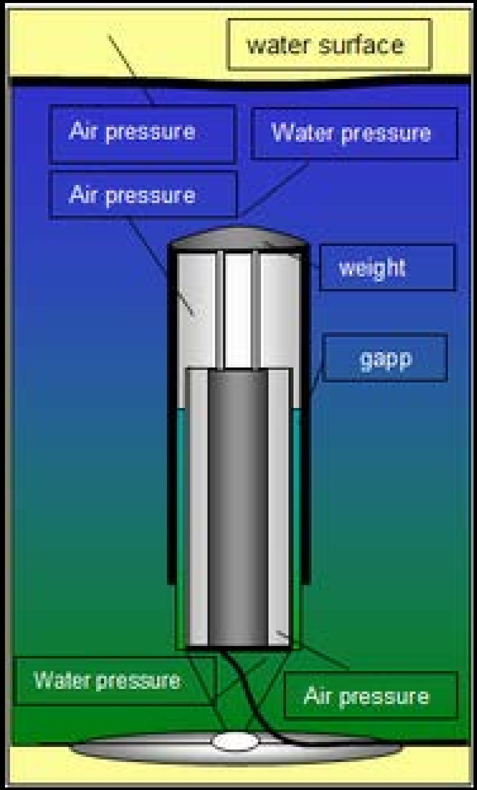
- prototype testing in Nissum Bredning


IDÉPLAN - HANSTHOLM HAVN
PRESSEMØDE 29.01.2009
VILJEN TIL HANSTHOLM HAVNS UDVIKLING


HAVNEUDVIDELSE

Submerged Pressure Differential

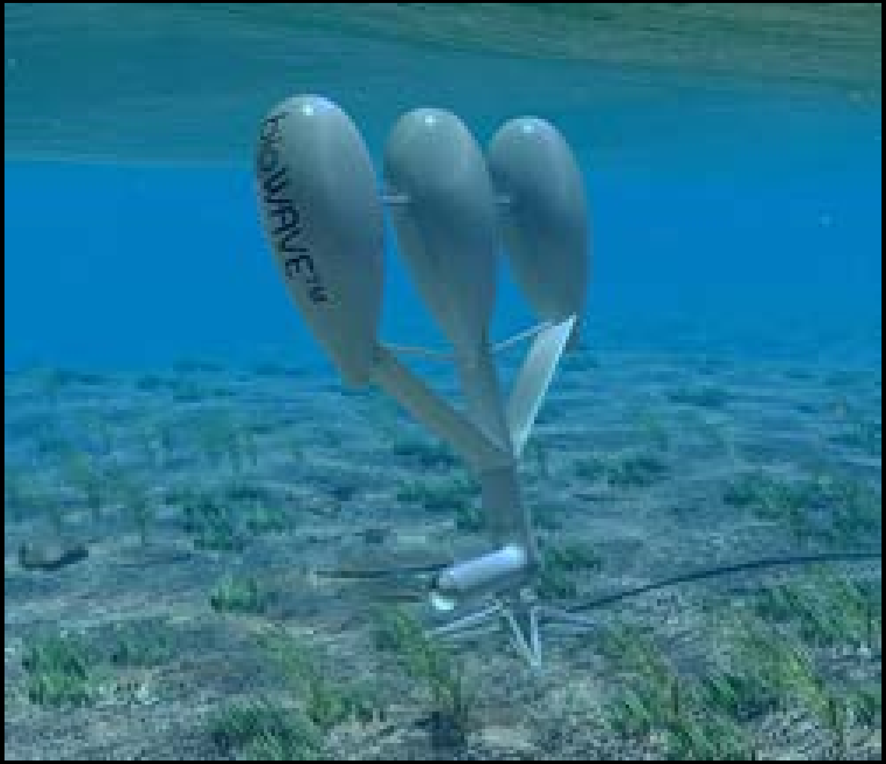
Archimedes Wave Swing (AWS)



Oscillating Wave Surge Converter

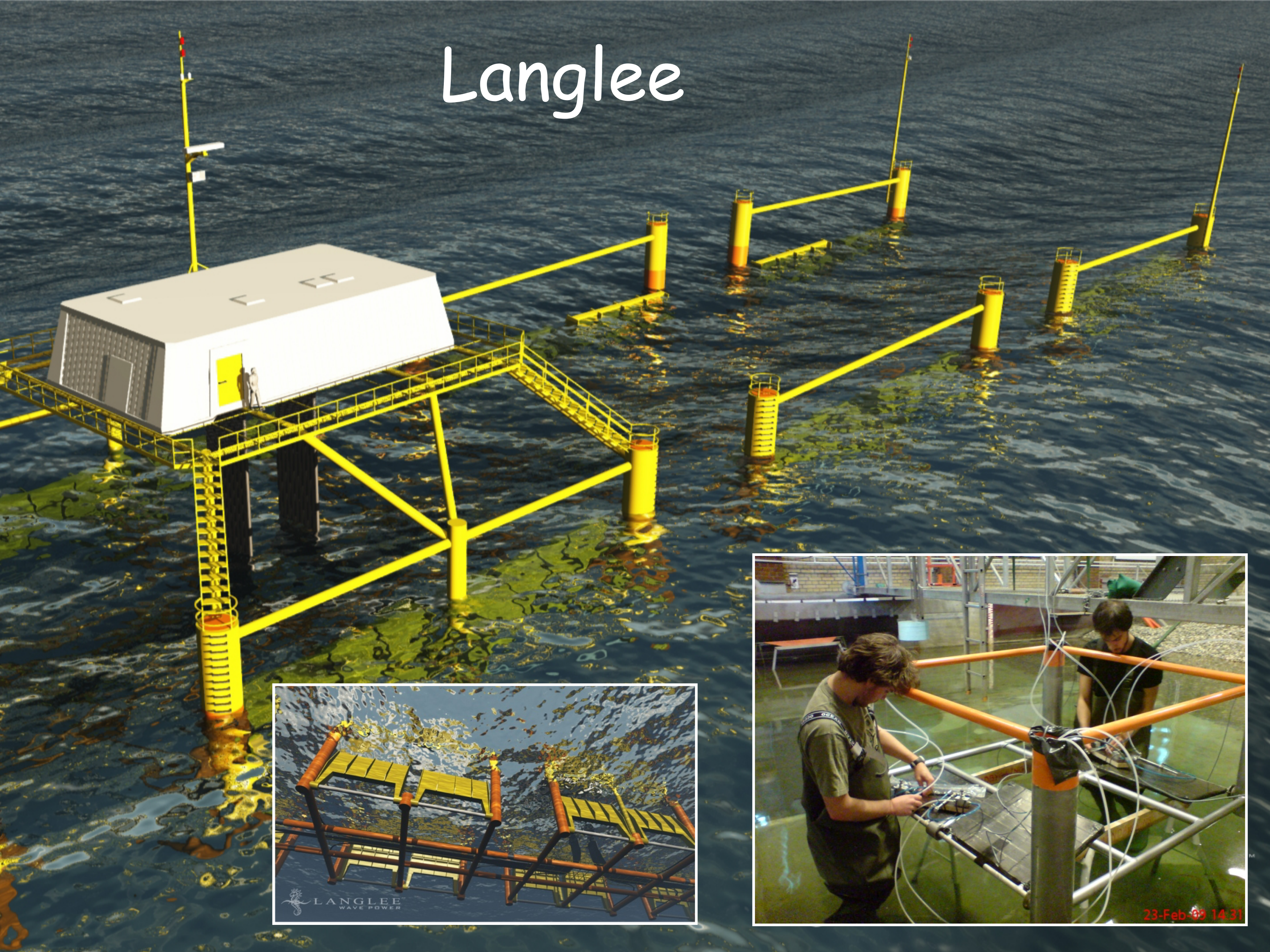
Wave Roller

bioWAVE



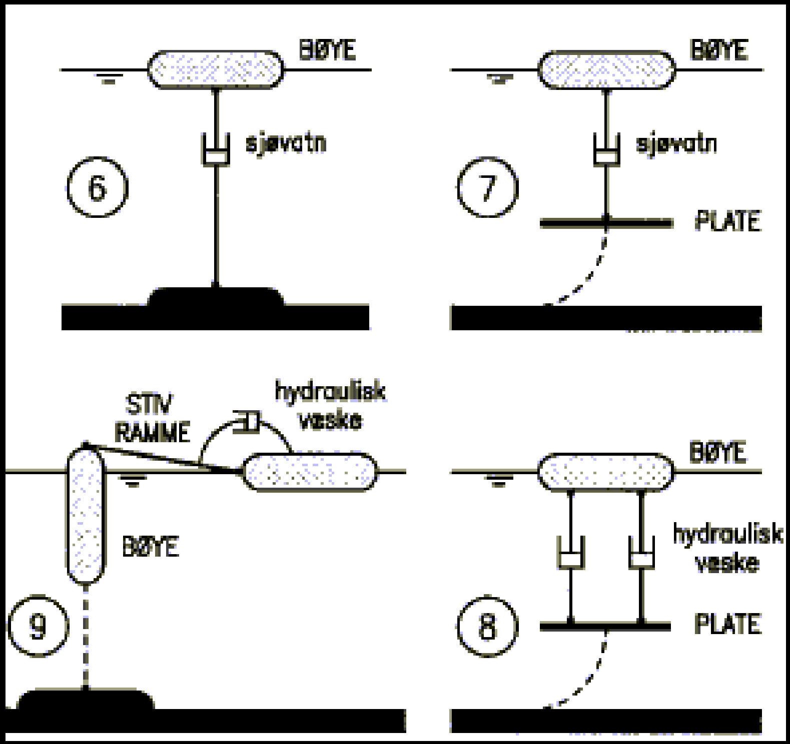
Oyster

Langlee



Point absorbers

Principle



Buoyancy Optimization

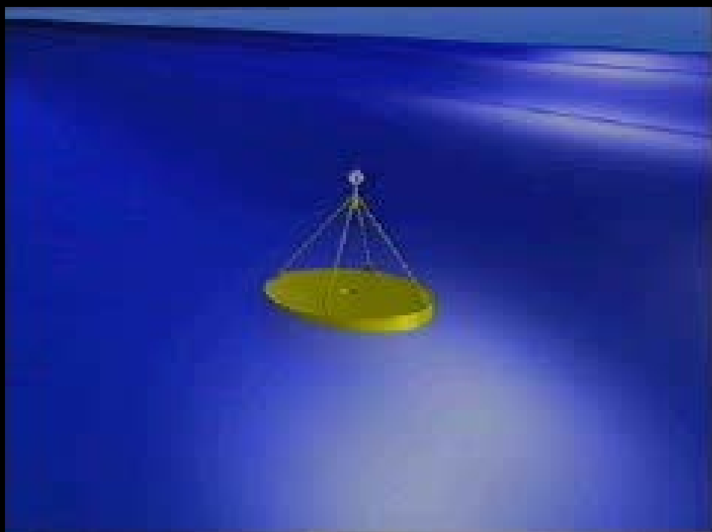
- Resonance
- Phase control

PTO

- Closed system, hydraulic
- Open system, seawater
- Direct drive

Point absorbers

Kim Nielsens point absorber



AquaBuOY

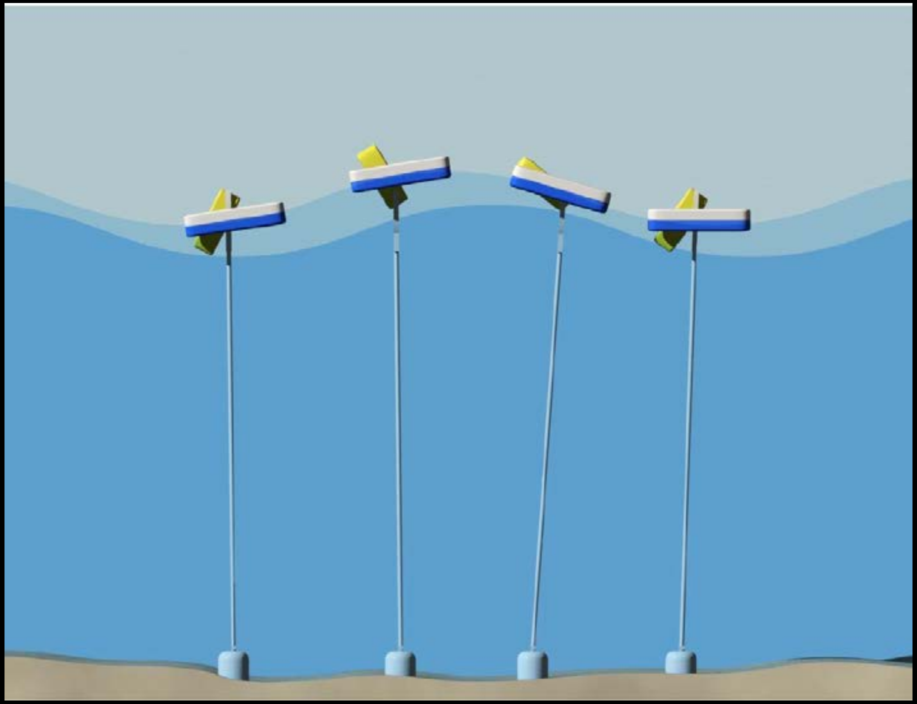
AquaEnergy Group Ltd.
Ocean Sustainable Electrical Power

PowerBuoy

OPT
OCEAN POWER TECHNOLOGIES

- Phased Development
- Demonstration Projects in Hawaii, New Jersey, site in Spain (10 WEC = 1.39MW)
- Proposed WaveHub Participant
- Unit Rating @ 150kW

Resen Waves - LOPF



CorPower

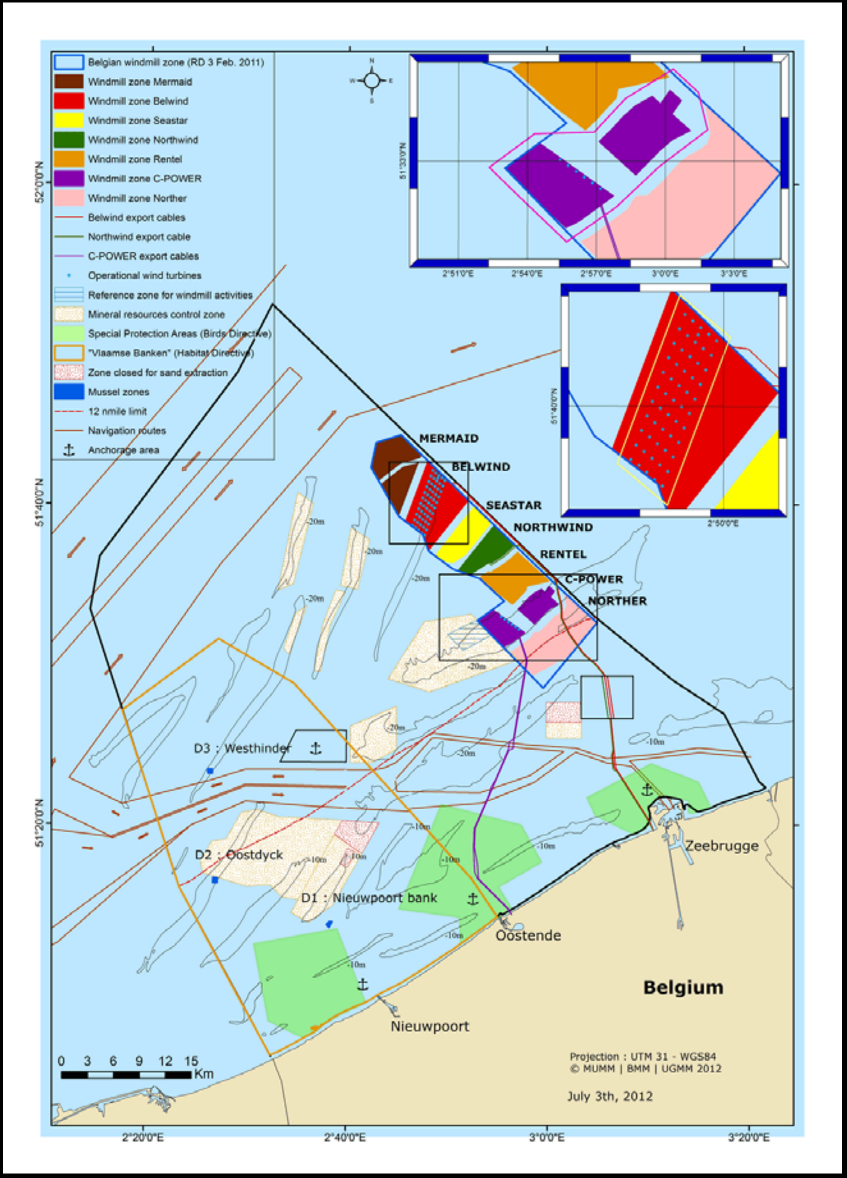
Includes WaveSpring technology
KIC InnoEnergy – HiWave project

FlanSea

Side note:

MERMAID, Belgium

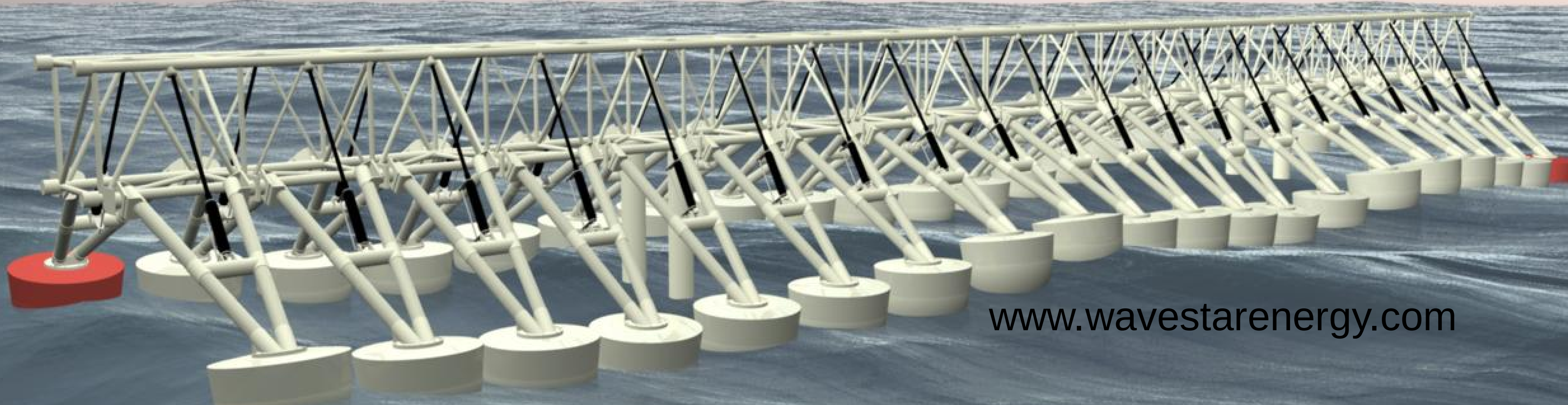
- 450 MW wind / 20 MW wave
- Creation of a market!



BOLT - Lifesaver

The wave energy converter *Wave Star*

A multi point absorber system

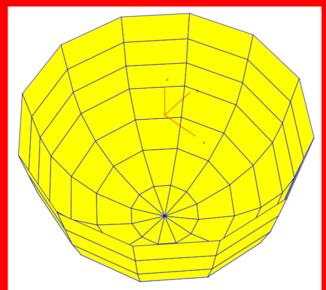


www.wavestarenergy.com

Scale 1:10 testing in Nissum Bredning

Scale 1:40 testing at AAU

Numerical modelling



Scale 1:10 Real Sea Tests in Nissum Bredning



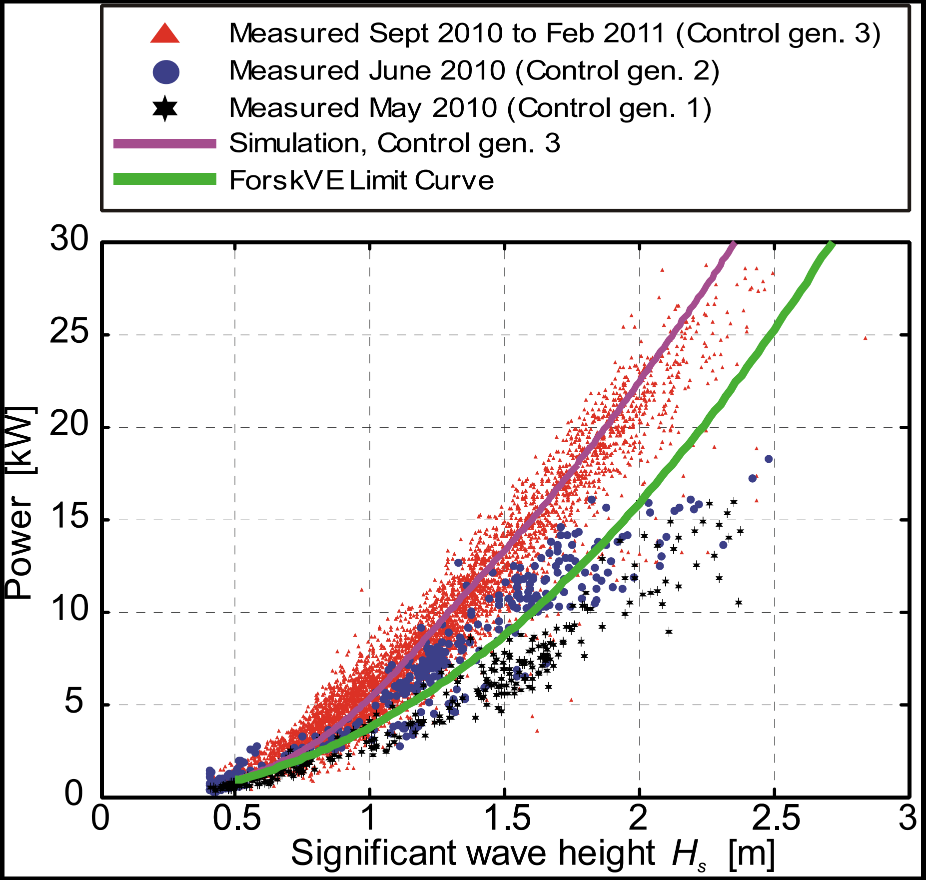


WAVE STAR ENERGY
WAVE STAR ENERGY

Power measurements from Roshage test unit

Notes:
- **Power is 10 minute average values of harvested power from one float (hydraulic power leaving one cylinder)**
- **A typical wave period for the Roshage location is used for the simulated curve**

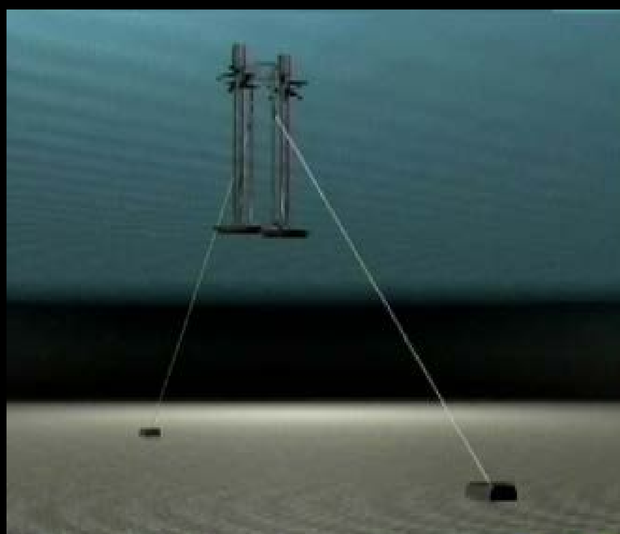
•Online data at http://wavestarenergy.com/concept

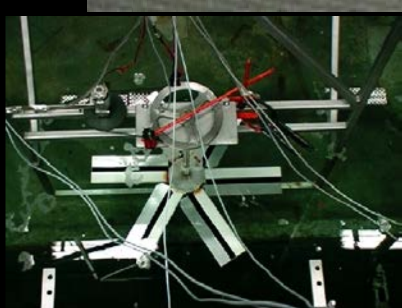


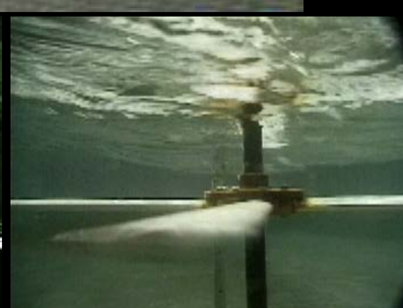
Floating Power Plant - Combined wind and wave

Wave Mills

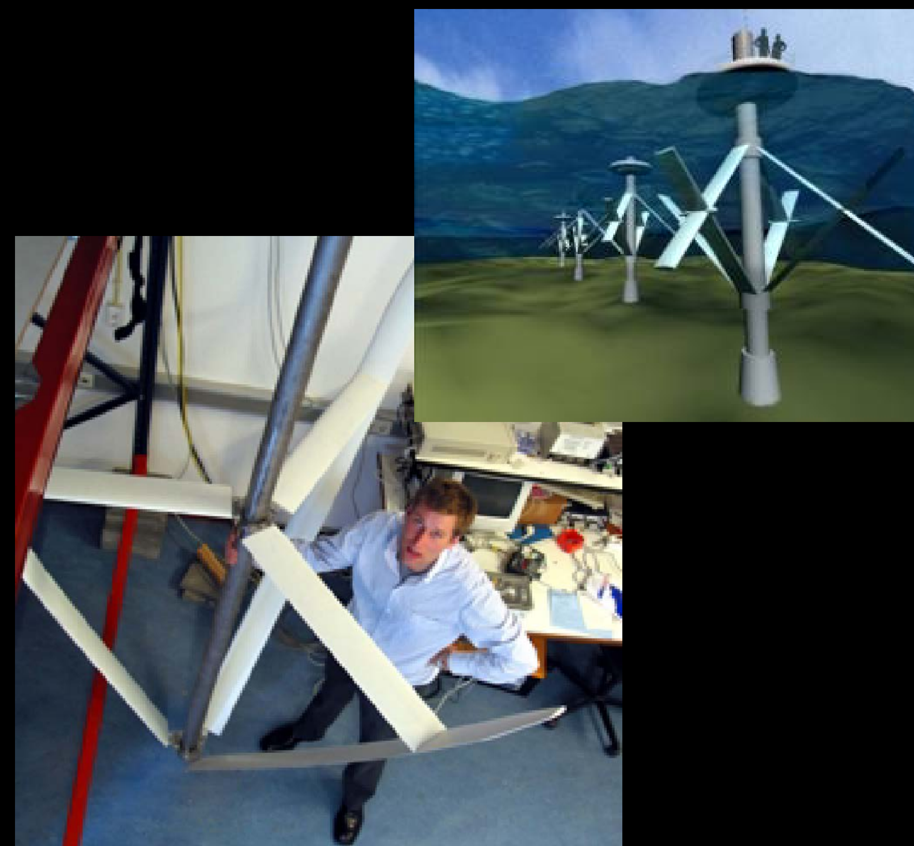
T. Basse





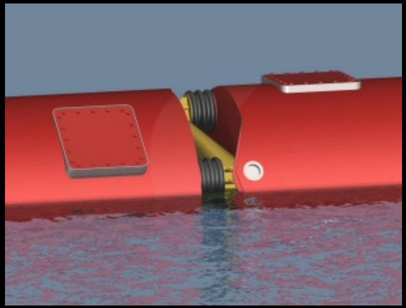


Wave Rotor

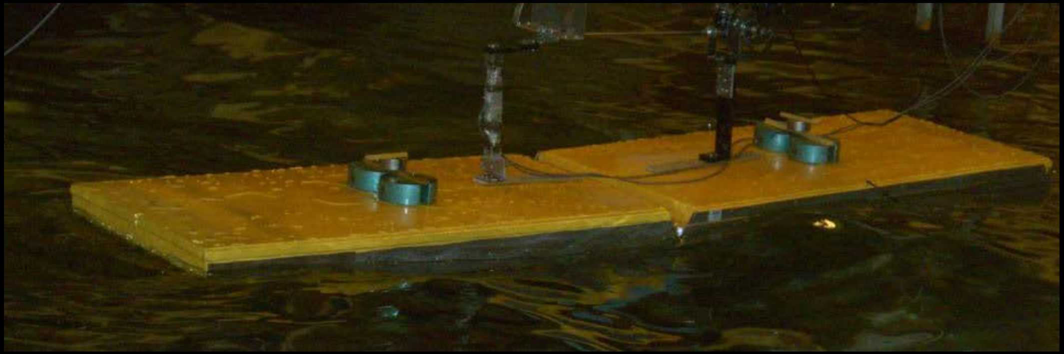


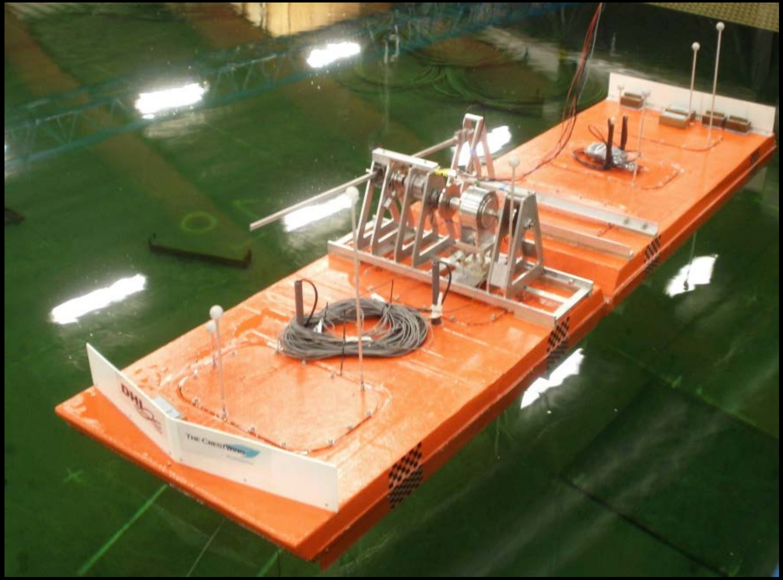
Attenuators

pelamis wave power



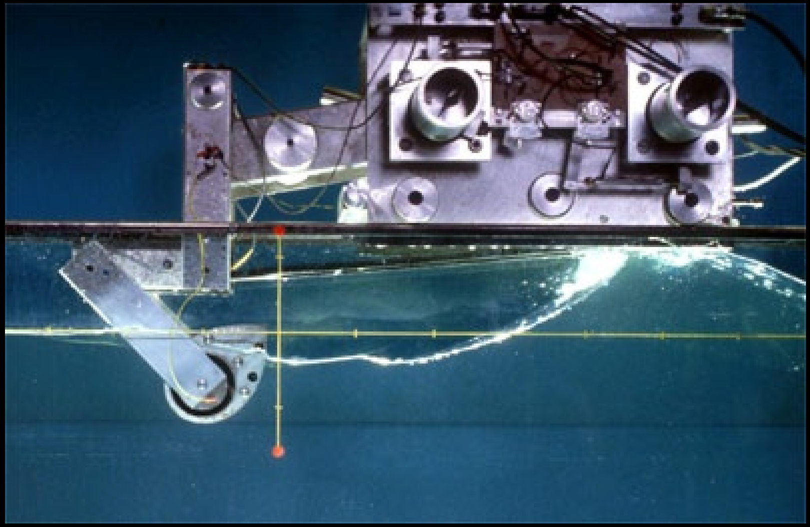
CrestWing





Terminators

Salters duck



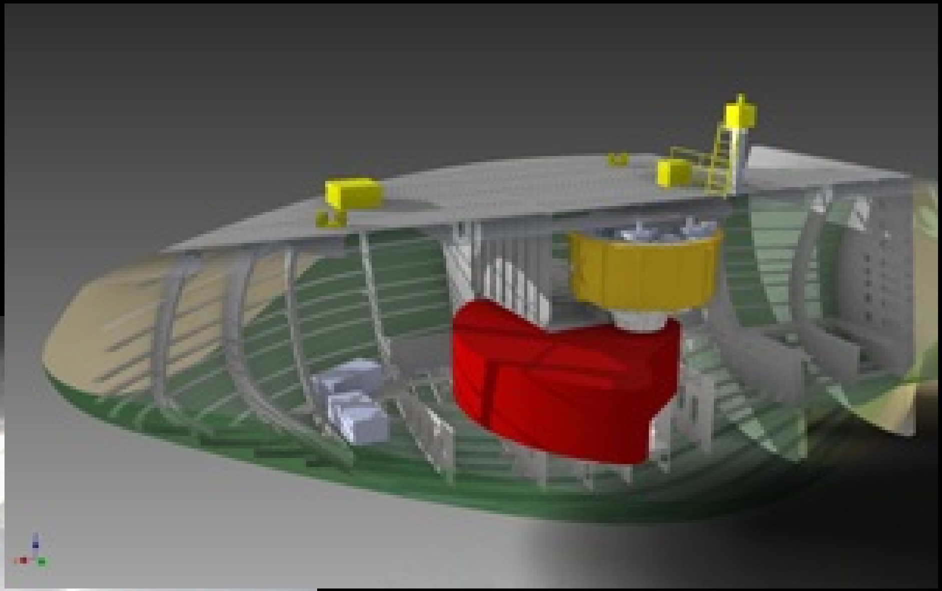
Eagle 1, 2 and 3 (GIEC – China)

1: 10 kW 2012-2014
2: 30 kW
3 100 kW
(max. average output)

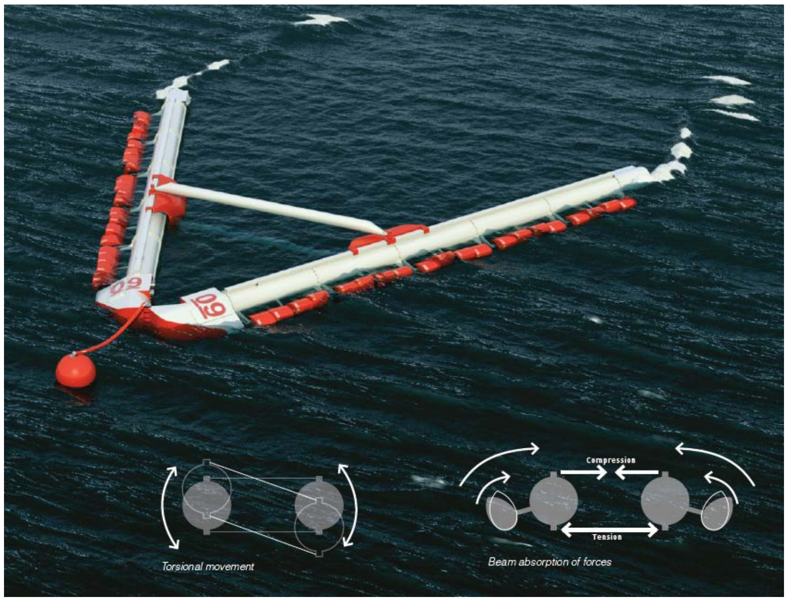
Azura WEC (USA)

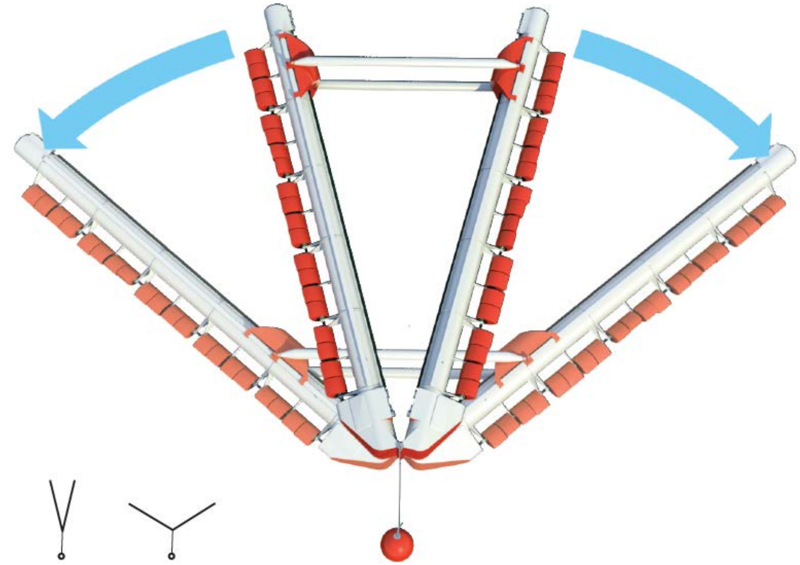
Wello Penguin

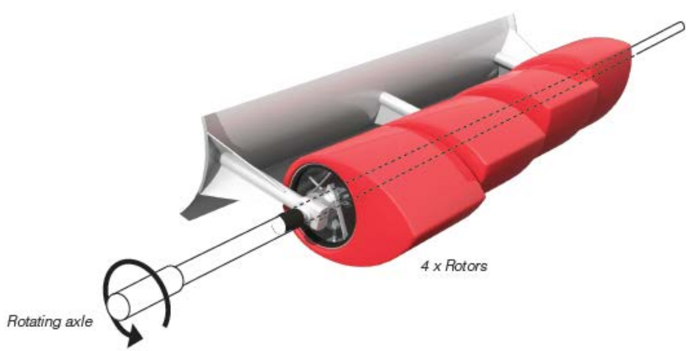
EC funding (€17 mill.) for testing at WaveHub

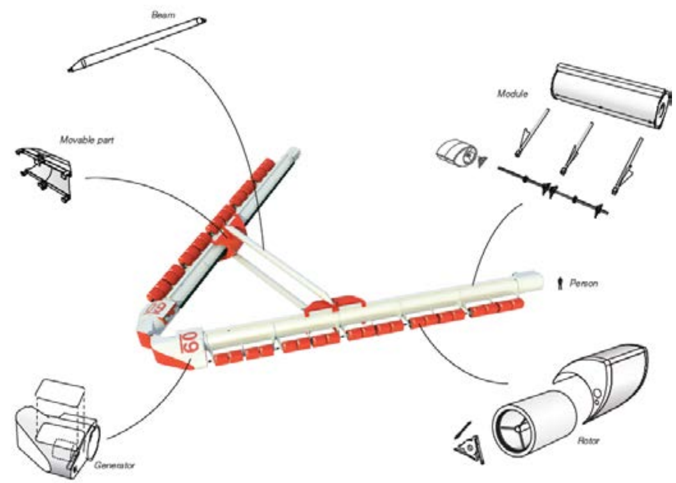


Weptos

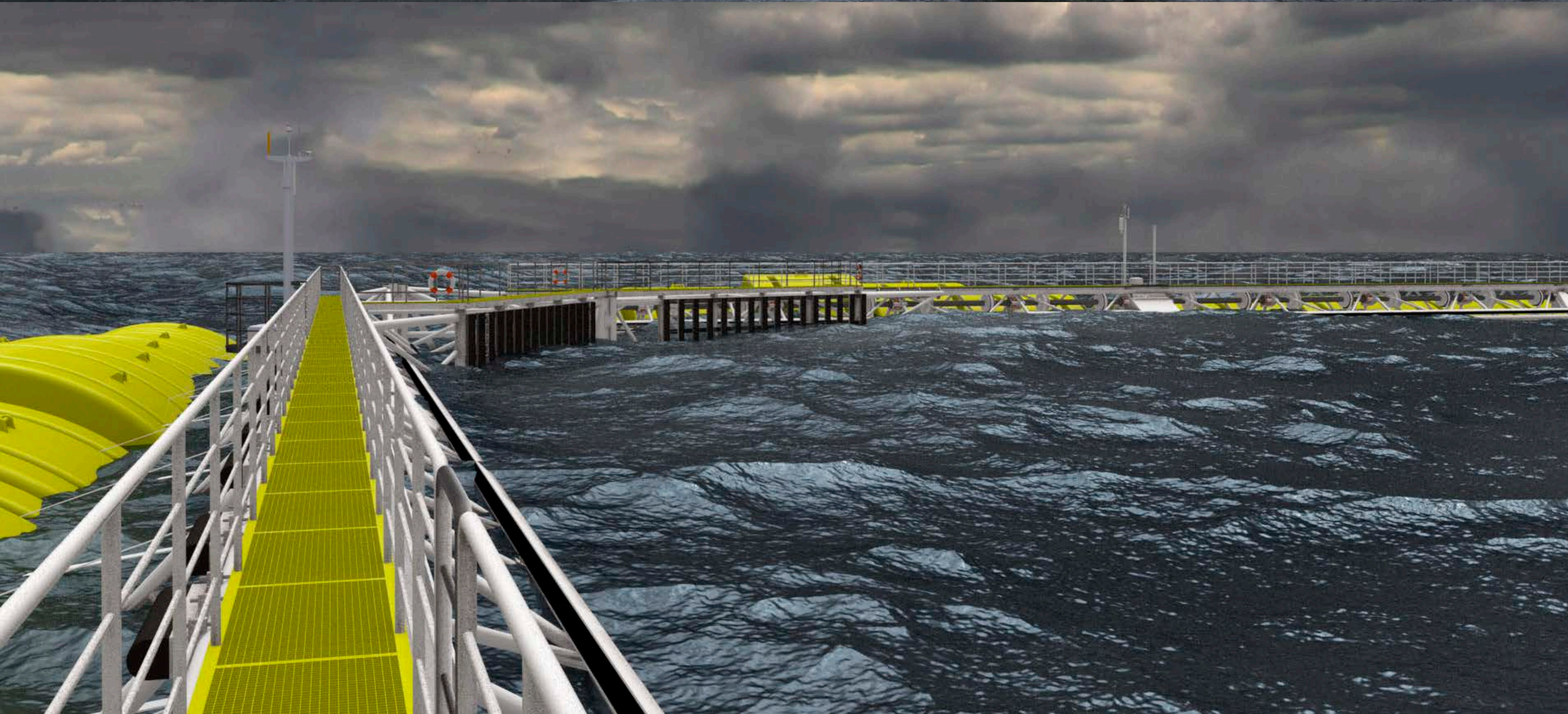

Torsional movement
Compression
Tension
Beam absorption of forces


Large waves
min. 30°
Small waves
max. 120°

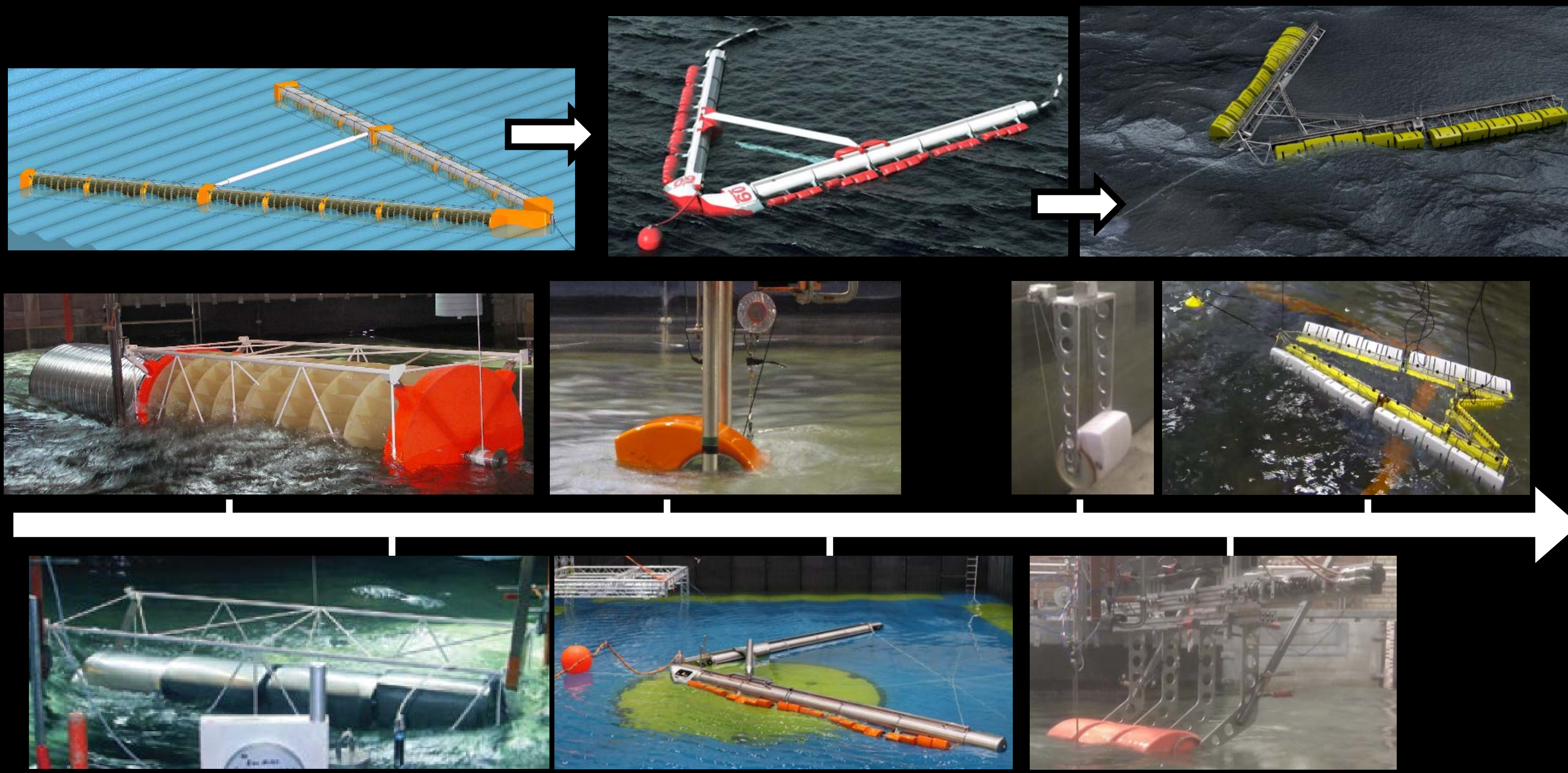

4 x Rotors
Rotating axle


Beam
Module
Movable part
Person
Rotor
Generator


WEPTOS



Research & Development

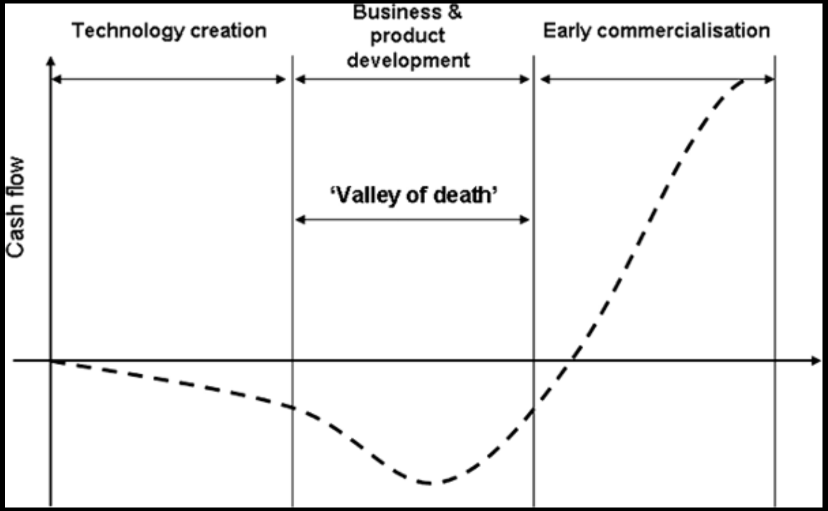


Very large numbers of ideas....

- Hundreds of concepts for utilization of wave energy – and even more patents!
- Still new concepts coming and being tested
- Some promising concepts, but the race is still open!
- No convergence so far...

And large challenges…

- Valley of death – spec. private cap.
- Very cap. intensive
- Small vs. large installations
- Market
- Externalities



Closing remark!

We are often asked
”Now you have been testing so many different devices – which one is the best?”

Not easy to answer! We can give reasonably good answers to what each of the tested devices is expected to produce, but the big question is ”at what price?”

We need devices in the real sea for a long period of time to get closer to answering that question!

References

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Questions - comments?

Thank you!